General Biology

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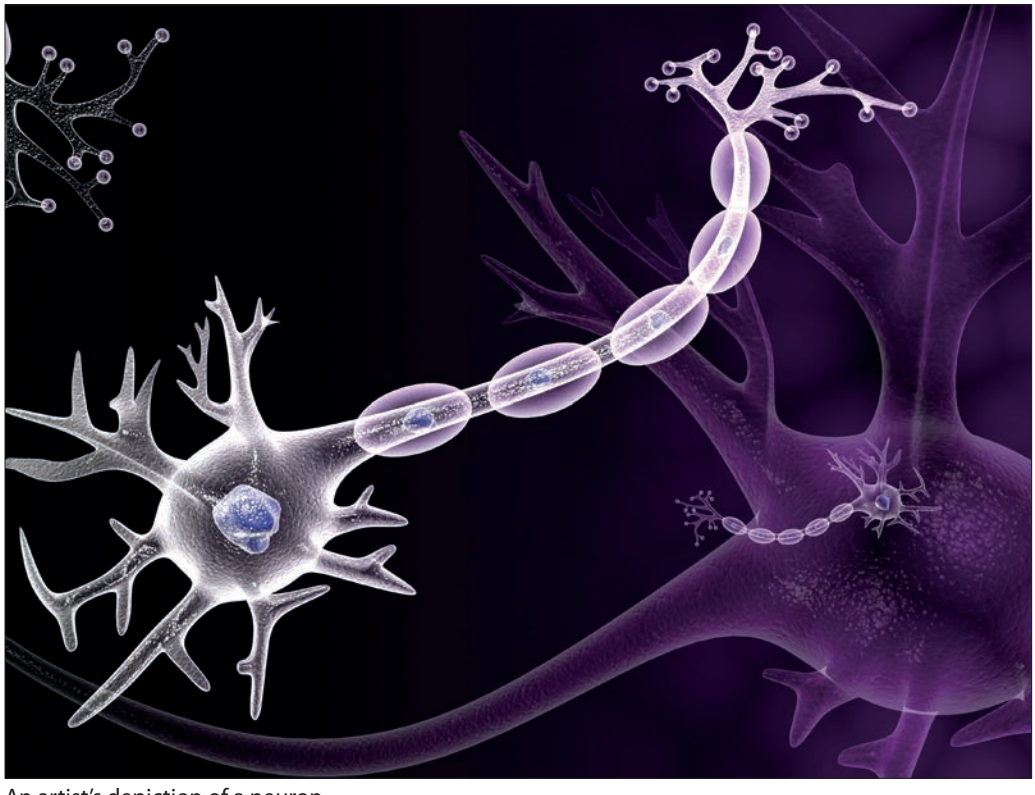
Chapter 1

Biology—The Study of Life



An artist's depiction of a neuron.

In 1906, Spanish scientist Santiago Ramon y Cajal won the Nobel Prize for showing that the nervous system is composed of individual cells, called neurons, rather than continuous nervous tissue. Just one of many diverse cell types that make up all living things, neurons have the amazing ability to transmit electrical impulses, enabling you to think, feel, and learn.

A neuron consists of three parts: the cell body (soma), the axon, and the dendrites. The soma is the central spherical part of the cell, containing the nucleus. The long arm protruding from the cell body is called the axon. The axon sends a signal to stimulate another neuron. Measuring as long as a meter, dendrites protrude from the cell body and are able to receive signals from other neurons. A single neuron can make thousands of connections with other neurons through its axon and dendrites. Throughout your study of biology, your neurons will actually form new connections. As you review and master each concept, connections between the corresponding neurons are strengthened. How amazing is it that studying the details of life (or any body of knowledge) actually alters the neural structure of your brain?

Objectives for Chapter 1

After studying this chapter and completing the exercises, you should be able to do each of the following tasks, using supporting terms and principles as necessary.

SECTION 1.1

1. Compare and contrast truth and facts.
2. Define *hypothesis*, *experiment*, and *theory*.
3. Describe each step of the Cycle of Scientific Enterprise.
4. Explain the roles played by magnification, resolution, and contrast in an image produced by a microscope.
5. Compare and contrast the images produced by light microscopes, scanning electron microscopes, and transmission electron microscopes.

SECTION 1.2

6. Describe in paragraphs the six characteristics of life, showing by each one how life exhibits purpose.
7. Explain how cells function as the fundamental building blocks of life.
8. Describe each level of biological organization and how each one incorporates all those beneath it.
9. Define *metabolism*.
10. Explain the roles of producers, consumers, and decomposers in the process of cycling matter and energy.
11. Describe the general process by which an organism grows and develops over its lifespan.
12. Give a specific example of an organism growing and developing.
13. Compare and contrast asexual reproduction and sexual reproduction.
14. Define *DNA* and *macromolecule*.
15. Briefly explain how organisms use and transmit genetic information.
16. Describe an example of an organism responding to a stimulus.
17. Describe homeostasis and give an example of an organism maintaining it.
18. Describe the process by which populations adapt to changing environmental conditions.

SECTION 1.3

19. Distinguish between spontaneous generation, archebiosis, and abiogenesis.
20. Describe Aristotle's thoughts on spontaneous generation and how Redi's experiments contradicted this line of thinking.
21. Explain how Needham's and Spallanzani's experiments supported or weakened the theory of spontaneous generation.
22. Describe Pasteur's experimental setup and his conclusions in detail.
23. Name the four scientists who debated the nature of spontaneous generation during the 1860s and describe their arguments and/or experiments.
24. Using the Cycle of Scientific Enterprise as a guide, trace the development of biogenic theory, explaining how each subsequent experiment either supported or modified the currently accepted theory.

1.1 The Science of Biology

You are about to undertake a great adventure—the study of *biology*. Biology is the science in which the nature of life is studied. However, defining life is not easy. In fact, it is one of the great questions that has been debated throughout scientific history. In order to define life, we first need some scientific skills in our toolboxes. Because biology is a science, it is important that we understand what science is and how science works. In the following sections, we review the nature of science and scientific knowledge.

1.1.1 Truth and Facts

The word *science* comes from the Latin *scientia*, meaning "knowledge" or "way of knowing." It is important to understand that there are different kinds of knowledge and that scientific knowledge is one kind. Another kind of knowledge deals with truth, which we address first.

Figure 1.1. One way to know truth is through direct experience, such as my direct knowledge of my family, shown here at the beach.

Truth can be defined as the way things really are. You can know truth either by direct experience or by revelation from God.[1] God's revelation can be further divided into Special Revelation (the Bible) and General Revelation (creation).

As an example, I can say that the following statement is true: "I have a husband and five children." This is a true statement about me, the author. From my own direct experience, I know that my husband and five children, pictured in Figure 1.1, are the other members of my family. I can count them, I see them every day, and I plainly remember the day I got married and the day each of my children was born. Those who know me personally can also testify to the truth of this statement.

A second example of a true statement is: "God made the world." This statement is true because God reveals it to us in the Bible, shown artfully in Figure 1.2. Genesis 1:1 tells us that "In the beginning, God created the heavens and the earth." Scores of other passages in Scripture reinforce the truth that creation is a work of God. In addition to this Special Revelation through Scripture, the lovely photo in Figure 1.3 reminds us that we also understand through General Revelation that God created the world. General Revelation is the way God speaks to all people through what He has made. As we look up into a clear night sky and see the vast array of stars, as in the view of the photograph, we know

Figure 1.2. Special Revelation, or God's Word, is one way that God directly reveals truth to us.

1 According to classic philosophy, a third way to know truth is by valid reasoning or logic from true premises, but we do not explore this further here.

that a higher power, infinitely more powerful than we are, is the cause behind such beauty. Many other majestic aspects of nature and its study convey this same truth. Indeed, in Romans 1:20 the Bible itself affirms that God speaks to us through General Revelation: "For his invisible attributes, namely his eternal power and divine nature, have been clearly perceived, ever since the creation of the world, in the things that have been made..."

Figure 1.3. General Revelation is another way that God directly reveals truth to us. This image shows a vast number of stars as well as the Milky Way Galaxy (on the left) as viewed from earth.

Scientific *facts* represent a type of knowledge that is different from truth. Illustrated in Figures 1.4 and 1.5, a fact is a statement based on evidence from many experiments or observations that is correct so far as we know. Experiments are carefully designed tests that are meant to give us further information about how the world works. Because we are constantly learning new things about the world, scientific facts can and do change. You may have already studied the Copernican Revolution, the paradigm shift that occurred as Copernicus and Galileo overturned the geocentric theory of the solar system. Before that, everyone accepted the fact that the sun orbited the earth. Today, everyone accepts the fact that the earth orbits the sun.

Figure 1.4. Experiments are one way that we obtain facts. This picture shows a scientist using a micropipette, an instrument designed to transfer tiny, precisely measured volumes of liquid.

As we do research, we come closer and closer to understanding the truth about the nature of the atom, the composition of cells, or the manner by which genetic change occurs over time. Yet, the truth about these subjects is not plainly evident to our everyday experience, and so the only way we can learn about them is through experiment and observation. Only God knows the whole truth about every aspect of his creation. We can only discover scientific facts that are correct so far as we know, and seek to account for the facts by the scientific theories we develop. As time progresses, hope-

Figure 1.5. Observations are another way we obtain facts. Scientists carefully watch and measure organisms in their natural environments. They may also collect samples for further testing.

fully these facts—and the theories that explain them—move closer and closer to the truth. Yet, as limited humans, there will always be the potential for adjustments to our knowledge as we investigate the world.

1.1.2 Theories, Hypotheses, and Experiments

A *theory* is a mental model or representation that accounts for a large number of scientific facts in an organized way. A theory is judged to be successful when it is repeatedly tested and shown to be consistent with the current body of facts (that are correct so far as we know). If new facts are discovered that do not support a theory, the theory must be reevaluated or revised. The main goal of science is to develop robust and successful theories. To quote textbook author John D. Mays, "Theories are the glory of science." Our goal as scientists is to build successful mental models that accurately describe the way the world works.

You may have heard the word *hypothesis* defined simply as a guess as to the outcome of a test or experiment. However, a hypothesis is not a random guess. Hypotheses are informed predictions, based on a particular scientific theory. Hypotheses are tested and supported (or not supported) by observations and experiments. The results of these tests strengthen or weaken the theories on which the hypotheses are based.

1.1.3 The Cycle of Scientific Enterprise

The interplay between facts, theories, hypotheses, and experiments is evident in a diagram of the Cycle of Scientific Enterprise, shown in Figure 1.6. Currently known scientific facts are gathered together as part of a cohesive theory that explains most or all of these facts. A widely accepted theory may be understood as our best current explanation for a body of data (facts). The theoretical understanding of the natural world then allows scientists to make predictions about what would happen in as-yet untested circumstances. As noted above, these informed predictions are called hypotheses. A hypothesis is tested by an experiment. The experiment provides evidence that either supports or does not support the hypothesis. If supported, the theory is strengthened. If the hypothesis is not supported, further tests must be done, perhaps with revised experimental methods. If the experiments continue to fail to support a hypothesis, then the theory is weakened and must be reevaluated. If enough evidence challenging a theory is collected, then a revised theory may be needed. Occasionally, a theory must be thrown out altogether and replaced. As time progresses, the cycle proceeds on and on, hopefully giving us facts and theories that are closer and closer to the truth about reality.

We are making a subtle point here about scientific knowledge that needs to be repeated and emphasized. Scientific theories are models. A widely accepted theory is the scientific *best explanation*. But in principle, theories are provisional; they are always subject to change as new information becomes known. Thus, theories are not truth claims about nature. In fact, since we are not God, we do not know the actual, whole truth about nature. So we continue to explore and learn more about the nature of reality indefinitely, continuing the Cycle of Scientific Enterprise. All scientists agree (and hope) that as we learn more and more, our theories grow closer and closer to the actual truth. If we actually do hit on the truth, we have no way of knowing it. All we know is that we have a theory that repeatedly produces hypotheses that are supported by experiment and observation.

As a quick example, consider the atomic theory that all matter is composed of atoms. Is this the truth? We do not know. We do know that this theory has stood up under the most rigorous and sophisticated tests for over 200 years, so we are pretty confident in the claim that matter is made of atoms. Most of us probably believe the claim to be true. But there could come a time when we discover that matter only appears to be composed of atoms and that something else is going on—that matter is composed of strings or loops or springs or has some crazy structure we have never even imagined.

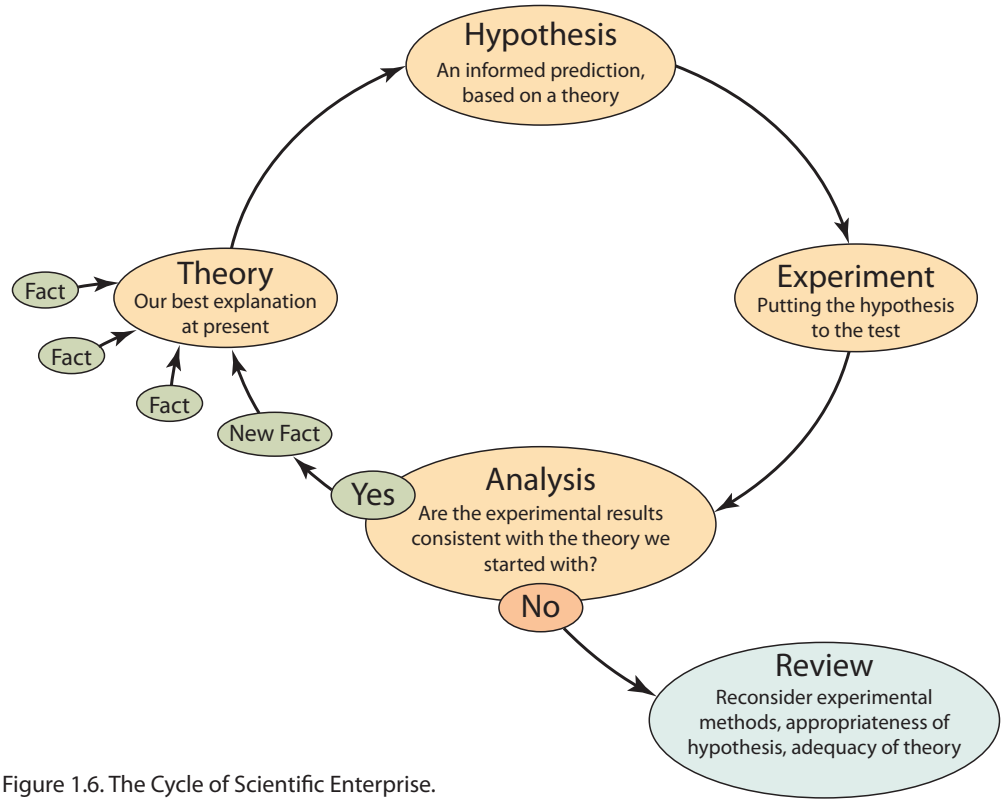


Figure 1.6. The Cycle of Scientific Enterprise.

You use the Cycle of Scientific Enterprise in your everyday experience. As an example, imagine you are home alone and you hear a loud chirping noise. Your perception of that noise is an observation you seek to explain. The theory you must work with includes the facts that there are several smoke detectors in your house capable of making such a sound, that a detector only chirps when the battery needs to be replaced, and that it has been a while since you changed any batteries on these detectors. So you form the hypothesis that one of them has a low battery and is alerting you. One by one, you inspect the battery-life indicator on each detector; this is the experiment that tests your hypothesis. All the batteries seem to be fine, so your hypothesis is not supported by the evidence. Assuming that your battery tests are correct, this experimental result indicates that your theory may need revising. The detector chirps again. Since no detectors indicate a dead battery, you must now form a new hypothesis. Perhaps there is an explanation for a chirping detector other than a weak battery? You go downstairs, following the sound of the chirp. This leads you to the carbon monoxide detector. You read the side label on the detector and realize that the chirping sound indicates a moderate level of carbon monoxide in your house. A new fact has been revealed,

Figure 1.7. A scientist presents the results of his experiments to a group of other scientists. Great progress is made as scientists engage with and build upon one another's work.

and your theory revised accordingly. With the revised theory, you act quickly to open windows, get outside, and call the fire department.

In the scientific world, the Cycle of Scientific Enterprise repeats itself as many thousands of scientists conduct research, publish papers, and engage with one another's work, as illustrated in Figure 1.7. Truly, science is an exciting, ever-changing field, with new discoveries made every day, all over the world. As we continue, let's now examine some of the instruments biologists use to make these important discoveries.

1.1.4 Instruments and Measurement

The study of biology relies heavily on a number of specialized instruments and techniques. One of the most important of these instruments is the microscope, which enables one to see organisms too small to be perceived by the naked eye (*microorganisms*).

Figure 1.8. Magnifying glasses bend light so that objects appear to be larger than they really are. The magnification of a simple lens such as a magnifying glass is limited to about 2×.

Magnifying devices have been part of recorded history since the time of the ancient Greeks (circa 400 BC). These simple devices consist of a single convex lens that bends light, creating a magnified image of the object being viewed. No doubt you have used a magnifying glass to observe objects more closely, as illustrated in Figure 1.8.

However, the *magnification* of these simple devices is limited to producing an image appearing about 2× larger than the object's actual size. Magnification is defined as the ratio of an image size to the object's actual size.

The first *compound light microscopes* were invented in the late 1500s in Holland. These microscopes were the first to use two lenses in order to achieve higher magnification than that of a single lens. The basic compound microscope works the same way a simple telescope does: a telescope makes a distant object that appears small appear larger, while a microscope makes an object that really is small appear larger. A typical compound light microscope, similar to what you might see in a biology classroom, is shown in Figure 1.9. This instrument allows you to see organisms at varying magnifications, usually in the range of 40–1000×.

Figure 1.9. Compound light microscope. Instruments such as this provide magnifications of 40–1000×.

Despite the higher magnification of the early compound light microscopes, their *resolution* was quite limited. Resolution is a measure of how clearly the image of an object appears. Mathematically, it is the measure of the minimum distance that two objects can be separated and still be viewed as distinct objects. If you wear corrective lenses, you may already be familiar with this concept. Without your contacts or glasses on, two distant objects near one another may appear to be blurry or fuzzy, melding into a single unclear image. However, with your contacts on you see two separate sharply focused objects.

The first light microscope to achieve both high resolution and magnification was that of Dutch scientist Antonie van Leeuwenhoek in the 1670s. This revolutionary breakthrough opened up the world of microorganisms—previously unknown to mankind.

While the light microscope is incredibly useful for viewing cells and microorganisms, its resolution is limited to about 200 nm (nanometers), or 2.0×10^{-7} m. This limit is due to the wavelength range of visible light (400–700 nm), which limits the minimum distance between objects a microscope can clearly resolve.

Because of this resolution limit, the inner workings of the cell are too small to see with a light microscope. To remedy this problem, in the 1930s physicists Ernst Ruska and Max Knoll constructed an *electron microscope* with a resolution that far exceeds that of the light microscope. This type of microscope uses a beam of electrons, rather than light, to generate an image of a sample. In a previous science class, you may have learned that electrons exhibit both particle and wave behaviors (just as light does). The electron microscope exploits the wave nature of the electron, which exhibits wavelengths in the picometer (10^{-12} meter) range. The electrons are blasted at a sample at high speed. The interactions between the electrons and the atoms in the sample produce signals that are used to construct an image of the sample. The smaller wavelength of electrons (about 1000× shorter than the wavelengths of visible light) means that much higher resolution can be achieved—down to about 2 nm—and thus much smaller structures can be imaged.

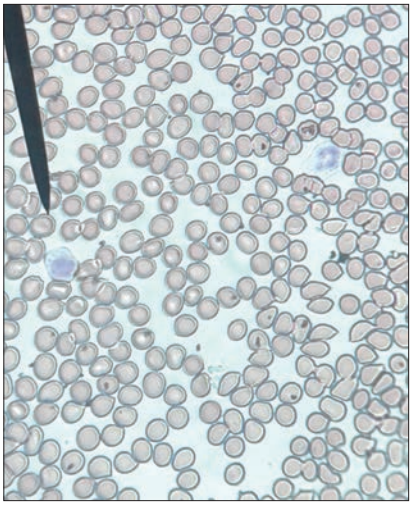


Figure 1.10. A light microscope image of human blood, stained with a special dye to increase contrast. Most of the gray-colored cells are red blood cells, which do not have a nucleus. On the left and right center of the image, you can see two purple-stained white blood cells. The nucleus of these two cells is visible, though not in much detail.

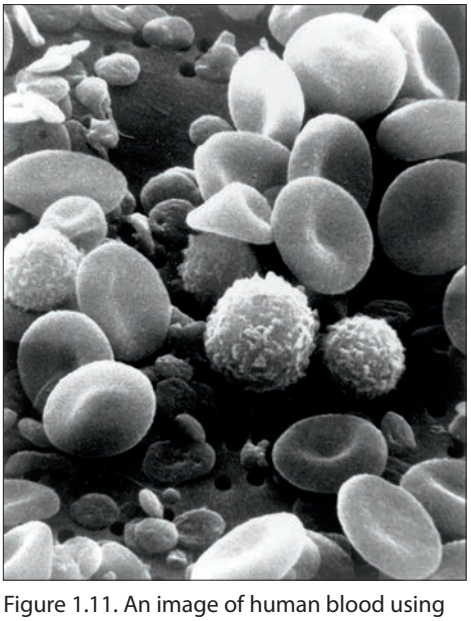


Figure 1.11. An image of human blood using an SEM. The donut-shaped cells are red blood cells, the cells that carry oxygen to each cell in the body. The rounder, large cells with projections on the surface are white blood cells. The tiny objects are platelets—cell fragments involved in blood clotting whenever there is an injury.

Figure 1.10 shows an image generated by a light microscope. This sample of human blood was stained with a special dye to increase *contrast*, in other words, to make the cells stand out from the background. Though the boundaries of the cells are clearly visible, other features are not. Figure 1.11 shows an image of human blood produced by a *scanning electron microscope* (SEM). Note that one can watch living things under a light microscope, but only non-living things can be imaged in an SEM.

Figure 1.12 shows an image produced by a *transmission electron microscope* (TEM). In this picture, the dark crescent shape is the cross-section of a single red blood cell, traveling through a capillary. Capillaries are tiny blood vessels where oxygen delivery and waste pickup occur throughout the body. We are looking at a cross-section of this capillary, as if we cut

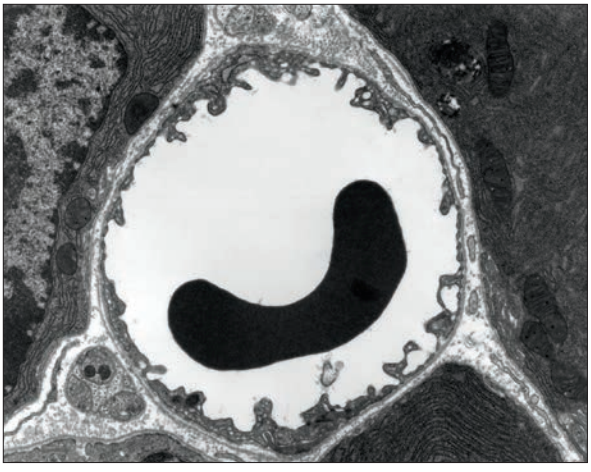


Figure 1.12. A transmission electron micrograph (TEM) of a red blood cell in a capillary (cross-section). The small diameter of a capillary forces red blood cells to pass through in single-file.

a thin slice of the tube and look at it end-on. This view is similar to looking into the end of a garden hose. That is why the capillary looks like a light-colored circle, rather than a long tube. Notice the rich detail, which enables the study of the surrounding cells (capillary walls are only one cell thick). Multiple organelles (small parts of cells that carry out specific functions) are visible within these surrounding cells. In contrast to three-dimensional SEM images, TEM images are two-dimensional. However, their high magnification and resolution allows for detailed images of organelles within cells, making the TEM an extremely powerful tool in biology.

In a previous science class, you may have learned about a form of microscopy with even higher resolution—able to image individual atoms. This technique is called *scanning tunneling microscopy* (STM). Instead of blasting an electron beam at a specimen from a distance, STM uses a tiny probe that is able to come extremely close to a surface. This close distance allows an electron to "tunnel" through the sample, imaging individual atoms on that surface. Since biologists are not usually concerned with such small samples, we do not address this technique any further here.

In addition to light and electron microscopes, there is a host of other instruments and techniques that are useful to biologists. We address some of these experimental techniques in later chapters.

Finally, you may have noticed that I throw around measurements and metric units like it's no big deal. It is important that we are able to measure lengths and other parameters in order to study living things accurately. In the United States, we commonly use units such as miles, inches, and feet. But scientists all over the world use the *SI* or *metric system* of units. So far, I have assumed that you are already familiar with this system. However, for some this may not be the case. If you need an introduction to the metric system, you can find that information in Appendix A. Table 1.1 shows the metric prefixes commonly used in biology. You should commit these to memory, if you haven't already done so.

The symbol μ is the Greek letter *mu*, and merits some comment. We pronounce μm "micrometer" (MY-kro-mee-ter), which is not to be confused with a tool for making small measurements called a micrometer (my-KROM-it-er). However, in biology, this measurement is so common that the micrometer has a special nickname—the *micron*. In fact, the symbol μ is sometimes used by itself to mean a micron (equivalent to micrometer). Therefore 1 μ (one micron) is the equivalent to 1 μm (one micrometer, which can also be read as one micron).

Another unit of measure commonly used in biochemistry is the *angstrom*. An angstrom is equivalent to one ten billionth of a meter (10^{-10} m) or one tenth of a nanometer (0.1 nm). The angstrom is not an official unit in the SI system, but it is a handy unit of measurement because many individual atoms and chemical bond lengths are about an angstrom wide. This unit of measure is named after Swedish spectroscopist Anders Jonas Ångström (1814–1874).

Prefix	Abbreviation	Mathematical Equivalent	Level of Biological Organization	Example Application
kilo	k	10^{3}	biosphere	circumference of earth, ~10^{4} km
centi	c	10^{-2}	organism	average human height, ~180 cm
			organ	width of human heart, ~10 cm
milli	m	10^{-3}	tissue	width of largest human vein, ~24 mm
micro	μ	10^{-6}	cell	cell, ~5–120 μm
nano	n	10^{-9}	biomolecule	biomolecule, ~10–1000 nm
angstrom	Å	10^{-10}	molecule	average length of a chemical bond, ~1 Å
pico	p	10^{-12}	atom	typical atomic width, ~100 pm

Table 1.1. Metric prefixes commonly used in biology.

1.2 What is Life?

1.2.1 Life vs. Non-life

Now that we have discussed what science is, how science works, and some of the important tools and measurements that biologists use, it is time to explore the nature of life.

"Is it alive?" is a question that even the youngest of children ponder. My 5-year-old daughter recently asked me, "Are earthquakes alive?" It was a good question, and not only because we live in Southern California where earthquakes are common. Earthquakes move, can cause massive damage, and act without apparent cause.[2] Nonetheless, earthquakes are not alive.

So then, what is it that makes something alive? Just like an earthquake, you move, cause damage (hopefully not very often!), and act according to your own will. Unlike an earthquake, however, you are composed of cells, undergo metabolism, grow, have the potential to reproduce, respond to stimuli, and adapt to the changing environment. All in all, the characteristics that distinguish life from non-life are summed up in one word—*purpose*.

Let's take a minute to unpack what the word purpose means and how purpose is distinct from the design evident in the physical (non-living) world.

In the Physical Science text that is sister to this text, the author states that the universe is comprised of three basic things—matter, energy, and intelligence.[3] Matter is anything that has mass and takes up space; energy is what holds everything together and enables any process to happen; and intelligence is the wisdom of God or his creatures that causes everything to work together in an orderly and beautiful way. Since God created all that exists, his wisdom is evident everywhere, including in the laws of nature that govern how everything in the universe works.

In the study of life, we distinguish between non-living and living matter. Like everything else in the universe, living things are made of matter, use energy, and obey the laws of nature. However, non-living things do not act according to a guiding purpose as living things do. The

2 Of course, you learned in Earth Science that earthquakes are caused by the shifting of tectonic plates due to the buildup of stress. However, this cause was not apparent to my young daughter.

3 The most rigorously scientific way of describing this trio would be matter, energy, and order, where the order in nature is due to the laws of nature. The truth behind the order observed in nature is that this order is a manifestation of the intelligence of the Creator.

word purpose implies an end or goal (or, in Aristotle's language, a *telos*), such that everything a living organism does is aimed toward a singular, meaningful endpoint. Non-living matter does not behave in a purposeful fashion; it simply responds to physical processes.

Consider a common inanimate (non-living) object, such as a rock. The rock is made of atoms and molecules (matter). Its existence is the result of the God-given laws of nature (being formed by chemical reactions and weathering). It does not, however, act according to an innate purpose. If the rock moves, it is because an outside force acts on it. A living thing, on the other hand, has a guiding purpose that directs all its more specific characteristics. The simplest purpose a living thing can have is to survive and reproduce. Beyond this, organisms display more complex purposes such as supporting other life in an ecosystem. Finally, human beings have many purposes, including the most noble "chief end" of all: "to glorify God and to enjoy Him forever."[4]

Beyond the general characteristic of exhibiting purpose, all living things possess six specific characteristics, listed in Table 1.2. You can also think of these six characteristics as six requirements that must be met in order for a thing to be regarded as alive. Note that all six move an organism toward the fulfillment of its purpose. In the remaining subsections of this section, we examine these six characteristics in more detail.

To illustrate, my children were recently subjected to a dramatic experience that highlights the dividing line between life and non-life. At a school picnic, they excitedly participated in a number of games, winning three live goldfish in little plastic baggies. Not wanting to dampen their enthusiasm for their new pets, I invested in a small aquarium, colorful gravel, plastic plant-like decor, and a small pink castle, not to mention the required chemical additives to make tap water safe. We carefully transferred the fish to their new home, making sure that their baggies had time to adjust temperature so as not to shock the fish. At first, everything went along swimmingly (pun intended). Our three goldfish beautifully displayed to us that they were alive, displaying the characteristics listed in Table 1.2. Were they composed of cells? Check. Did they metabolize? Yes. They utilized matter and energy. We fed them diligently twice a day, and it was evident that they were producing excrement. They energetically swam back and forth, using the energy that the food gave them. Did they grow, develop, and reproduce? Though we didn't get to see it ourselves, as living things, these fish most certainly grew from small eggs. And my children most earnestly hoped that there might be both a male and female goldfish among them so that they might have babies. Did they use and transmit genetic information? Yes. They had genes that specified where exactly their fins should be placed, the bright orange color of their scales, and how they would breathe the oxygen dissolved in their tank water. Any of their offspring would have displayed similar traits. Did they respond? Yes, indeed! If they swam too close to a spiky plastic plant, they turned around and swam in another direction. If they swam underneath the "waterfall" produced by the filter water being returned to the tank, they swam more vigorously in order to stay on their intended path. Did they adapt to their environment? Here is where we ran into trouble.

After a few days, our goldfish friends began to behave strangely. One, whose name was Buddy, decided he preferred to hang out in one spot near the gravel. We could see his gills and mouth moving back and forth, though, so we knew he was alive. Another one, whose name was Buddy Jr., floated to and fro, but didn't exert the same energy that he once did. It was almost as though he became paralyzed, subject to the forces of the filter water alone. However, his gills and mouth continued to move, indicating that he was still alive. I looked for information as to why they might be behaving this way. Based on the best available "goldfish care theory," I came up with the hypothesis that their water had too much ammonia and needed to be partially changed. I set out to complete this change, making sure to place the correct number of drops of water

4 The "chief end of man," as described by the Westminster Catechism.

1. Living things are composed of cells and operate on many levels of organization.	Living things are made of matter, and are arranged according to highly organized, complex, purposeful designs. The most fundamental level of organization that displays all the characteristics of life is the cell.	Section 1.2.2
2. Living things metabolize.	Living things use materials from the environment and excrete waste, a process called metabolism. Waste products are broken down and used again. Energy is continually supplied from the sun, converted, and used by organisms, which produce waste heat in the process.	Section 1.2.3
3. Living things grow, develop, and reproduce.	Organisms proceed through various life stages, typically of increasing complexity, until maturity is reached and the organism is able to reproduce.	Section 1.2.4
4. Living things use and transmit genetic information.	Living things share a common genetic code, or instruction manual for life. These instructions dictate how an organism functions and are passed on to offspring.	Section 1.2.5
5. Living things respond.	Living things have some sort of sensory system by which they respond to light, sound, motion, or other stimuli. They process the information received and respond accordingly.	Section 1.2.6
6. Living things adapt to their environments.	Populations of organisms adapt to a changing environment, as each generation favors survival of organisms with the most suitable traits.	Section 1.2.7

Table 1.2. Six characteristics of life.

conditioner, and to equalize the temperature before adding the new water. Just minutes after the fish had their new water, I heard a distressed shriek coming from upstairs. One of my children saw that the goldfish were no longer breathing. Their gills and mouths were now completely still. Our pets had ceased living.

What happened? Most likely, the stress of being a carnival prize, being driven home in a baggie, and "lovingly" handled by a six-year-old child, followed by the shock of entering a new aquarium environment was too much for these sweet goldfish to handle. They could not adapt to the stressful environment, and then, one by one, lost all the other attributes of life.[5]

The living goldfish had purpose. They lived to survive and reproduce (and to bring delight to my children). The bodies of the deceased goldfish became non-living matter. They moved because of outside forces (like the filter waterfall), not of their own accord. Now laid to rest in backyard graves, their cells are decomposing into smaller building blocks. They no longer possess any of the attributes of life.

In the following subsections, we take a closer look at these six characteristics of life. In later chapters, we address aspects of these characteristics in much greater detail.

1.2.2 Cellular Structure and Levels of Organization

So far as we know, all living things are made of *cells*. Just as atoms are the fundamental building blocks of matter, cells are the fundamental building blocks of life. A cell is a self-contained living factory, surrounded by a barrier called a *membrane*, containing genetic material

5 If I had maintained a large population of goldfish in a much larger tank, perhaps a few fortunate ones might have survived the unfavorable water conditions. After several generations, all the resulting fish would have been much more resistant to the ammonia in the water.

Figure 1.13. A 3-D model of an animal cell. Cells range in size from 10^{-5}–10^{-4} meters across, and thus are only visible with the aid of a microscope. The genetic material (DNA) is shown in grayish-white around the center.

(instructions for operation), capable of self-replication, and keeping itself alive by cycling matter and energy. Rocks, air, water, cars, and computers are not made out of cells, and thus are not alive. Living things—such as bacteria, mold, trees, badgers, and human beings—are composed of cells. Figure 1.13 shows a generalized, cut-away diagram of a cell and its parts. Chapters 3–5 of this book are devoted to delving into the fascinating details of cells and how they work. For now, just note that living beings have cells as their fundamental unit—either as a single-celled organism or as many cells working together.

The fact that living beings are composed of cells illustrates a larger principle in biology—that life operates on many levels of organization, as illustrated in the four-page Table 1.3, containing Figures 1.14a–1.14l. These levels entail differing size scales (from the size of an atom to the size of the earth itself), and each higher level encompasses all the levels below it. At each step, higher

levels of complexity and more intricate interactions are present, illustrating how the creative power of God sustains life itself. These levels of organization are foundational to the study of biology, and you must commit them to memory.

The first thing to notice about Table 1.3 is that the smallest level of organization we depict in biology is the *atom*. Figure 1.14a shows a simplified diagram of a hydrogen atom. Atoms are the fundamental unit of all matter and are much too small to be imaged except by very advanced instrumentation. Matter in general (i.e., anything made out of atoms) is not necessarily alive, but it is important to know that all living things are ultimately made out of atoms.

As we discuss in Chapter 2, atoms join together (by sharing or transferring their electrons) to make molecules, as illustrated in Figure 1.14b. Simple molecules comprise compounds that you may encounter in everyday life, such as water, oxygen gas, carbon dioxide, or sodium bicarbonate (baking soda). These simple molecules are also very much active in biological processes—all of them are necessary to keep you alive. About 60% of your body's mass comes from water, you inhale oxygen gas and exhale carbon dioxide, and sodium bicarbonate regulates the acidity of your blood. However, simple molecules can also combine to form *biomolecules* (also called *macromolecules*), the next level of organization.

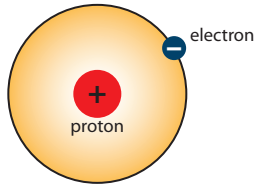
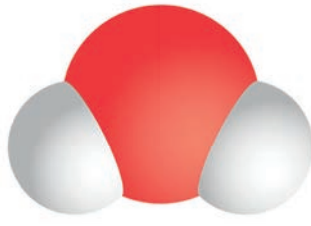
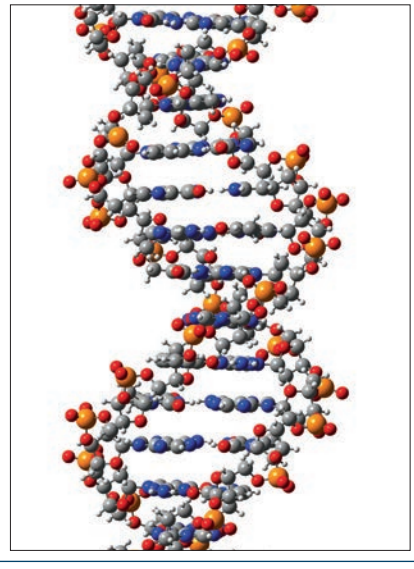
Many biomolecules are formed by repeating units of simple molecules, as illustrated in Figure 1.14c. This biomolecule is a fragment of genetic material called *DNA* that holds the operating instructions for the cell. Other biomolecules include proteins, carbohydrates, and lipids, discussed in Chapter 2.

The next level of organization is the *organelle* (Figure 1.14d). Organelles are small parts of cells that carry out a specific function. For example, one organelle, called the *nucleus*, is located at the center of the cell, and contains most of the cell's genetic material (DNA). I must pause here to clarify. You already know the term "nucleus" as the central part of an atom, the region holding the atom's protons and neutrons. The nucleus of a cell is a completely different thing, and in fact is many orders of magnitude larger than the nucleus of an atom. Their only common feature is being the centrally located portion of a fundamental building block—of either atoms or cells. Nonetheless, the nucleus of an atom is completely different from the nucleus of a cell, so take note and keep these terms straight.

Now, organelles are amazing because they are composed of different parts that work together. Going back to the example of the nucleus of the cell, several parts of the nucleus collaborate to control all the other cellular activities, making the nucleus the command center of the cell. Several types of biomolecules of different shapes and sizes are found in the nucleus. These parts intricately work together like a finely tuned factory, sending out messages that control what all the other organelles in the cell do. Every other organelle in the cell has a specific job as well, and we elaborate more on these roles in later chapters.

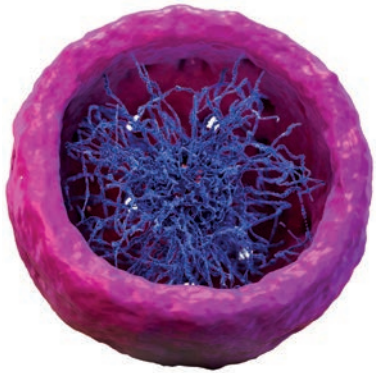
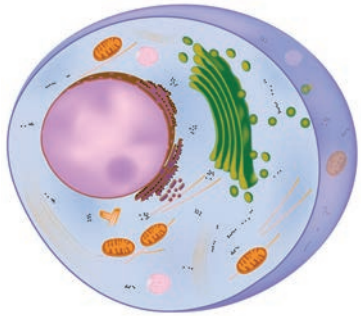
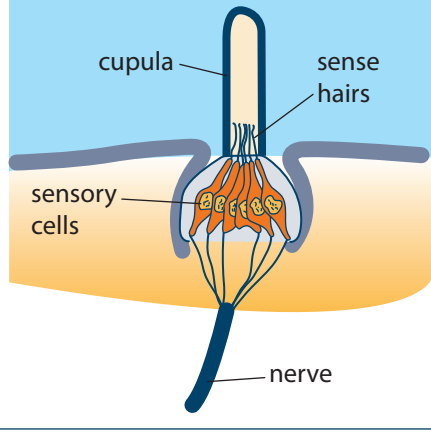
Although each organelle has different parts that work together to do a job, a lone organelle cannot be considered a living organism. Consider why this is the case. Let's return again to our example organelle, the cellular nucleus. By itself, does a cellular nucleus possess all six of the characteristics of life?

1. Is it made of cells? (no)
2. Does it cycle matter and energy? (partly)
3. Can it reproduce itself without the help of other organelles? (no)
4. Does it use and transmit genetic information? (yes)
5. Does it respond? (yes, molecular signals control how many messages are sent out based on environmental conditions)
6. Does it adapt? (possibly)

Level	Size scale (length or diameter in meters)	Illustration	Caption
*Atom	10^{-11}–10^{-10}		Figure 1.14a. An atom is the fundamental unit of matter, made of protons, neutrons, and electrons. Only 118 types of atoms have been found in creation, and are cataloged in the periodic table. This diagram depicts a hydrogen atom, which does not have any neutrons.
*Simple molecule	10^{-10}–10^{-9}		Figure 1.14b. Molecules are made by joining atoms together through the sharing or transferring of electrons. This illustration depicts a water molecule, which joins two hydrogen atoms (white) to one oxygen atom (red).
*Biomolecule	10^{-9}–10^{-7}		Figure 1.14c. A biomolecule (or macromolecule) is a large molecule that often consists of many repeating small molecules attached together. DNA, RNA, proteins, lipids, and carbohydrates are types of biomolecules. This image shows a small (13 base pair) segment of DNA.

*Note that by themselves, entities smaller than a cell are not alive. However, when put together in the organized, purposeful array of a cell, they comprise life.

Table 1.3. Levels of organization in biology. For items (f)–(k), fish are used as examples.

Level	Size scale (length or diameter in meters)	Illustration	Caption
*Organelle	10^{-8}–10^{-6}		Figure 1.14d. Organelles are groups of different biomolecules that work together to perform a function within a cell. This image depicts the nucleus of a cell. Present are the nuclear membrane (pink) and DNA (blue).
Cell	10^{-7}–10^{-4}		Figure 1.14e. Cells are the fundamental unit of life. Cells contain multiple organelles as well as DNA, and are enclosed by a cell membrane. These parts work together to perform all the functions of life (metabolism, reproduction, growth, response, and adaptation). The nucleus of this cell is shown in light pink.
Tissue	(varies)		Figure 1.14f. A tissue consists of many cells of the same type that work together in the body. In the center of this figure are several sensory cells that work together to sense pressure changes underwater in the lateral line of a fish. (The entire structure shown is called a neuromast.)

*Note that by themselves, entities smaller than a cell are not alive. However, when put together in the organized, purposeful array of a cell, they comprise life.

Table 1.3 (continued). Levels of organization in biology. For items (f)–(k), fish are used as examples.

Level	Size scale (length or diameter in meters)	Illustration	Caption
Organ	(varies)		Figure 1.14g. In an organ, tissues work together to perform a particular job that benefits the whole body. This picture shows the lateral line of a fish, where each of the dark spots lined up horizontally is one neuromast (illustrated in Fig 1.14f). The lateral line can sense pressure changes in the water.
Organism	10^{-7}–30		Figure 1.14h. An organism is an individual living being, composed of organs that work together to perform the functions of life. (Some organisms consist of a single cell.) This photo shows a parrotfish.
Population	(varies)		Figure 1.14i. A population is a group of organisms of the same species living in a particular region. This photo shows a group of parrotfish.

Table 1.3 (continued). Levels of organization in biology. For items (f)–(k), fish are used as examples.

Level	Size scale (length or diameter in meters)	Illustration	Caption
Community	up to 10^6		Figure 1.14j. A community consists of multiple, interacting populations in a particular region. This photo shows a number of fish species swimming in close proximity.
Ecosystem	up to 10^6		Figure 1.14k. An ecosystem is a community of living things that interact with nonliving components of their environment. Here are a number of fish and coral polyps that interact with water, sunlight, and calcium carbonate to comprise a coral reef ecosystem.
Biosphere	10^7		Figure 1.14l. The biosphere consists of all life on earth.

Table 1.3 (continued). Levels of organization in biology. For items (f)–(k), fish are used as examples.

Based on the first characteristic alone—that living things are made of cells—an organelle does not qualify as a living thing. But additionally, the nucleus of a cell doesn't completely cycle matter and energy (other organelles called the *mitochondria* are necessary to produce the chemical energy the organelle uses) and cannot reproduce itself. An organelle by itself does not include all the characteristics of life, but organelles specialize their roles so that an overall cell does include all the characteristics of life. It is for this reason that the cell is the lowest level of organization considered in and of itself to be alive. Another diagram of a cell is shown in Figure 1.14e.

Just as organelles specialize their roles in order to serve all the necessary functions of life for the cell, cells actually specialize their functions as well, to serve the needs of the entire organism—your body, for example. A group of cells of the same type that work together to perform a function is called a *tissue*.

In Figure 1.14f, we illustrate tissue with an example, found in most fish, called the *lateral line system*. As underwater creatures, most fish have a sort of "sixth sense" in that they are able to sense pressure and movement in the water. For example, if a crustacean swims nearby, a fish senses the resulting waves, and knows where to swim to find its next meal. In the center of the structure shown in 1.14f is a tissue composed of the hair cells that sense these very subtle changes in the water. This group of identical cells is part of a larger organ-like structure called a *neuromast*, which contains other cell types in addition to the hair cells.

Collectively, the tiny neuromasts comprise the lateral line, which is visible on the body of a fish and shown in Figure 1.14g. This lateral line is the *organ* responsible for the ability of a fish to sense water movement. This amazing ability helps fish to find prey, avoid predators, and stick together in groups.

An *organism*, or individual living being, is often made up of many coordinated organ systems. Figure 1.14h shows an individual parrotfish. Generally, an organism may consist of one or many cells. In the case of a many-celled organism, the cells stick together, forming specialized tissues and organs that coordinate their efforts so that the entire organism may survive and reproduce.

A *population*, or group of organisms of the same species living and interbreeding in the same area, is shown in Figure 1.14i. Populations do not exist alone, however. They often are part of *communities*—groups of populations living and interacting in the same area. These interactions could include both cooperation and competition, or even species eating (preying upon) others. Even if one species does not prey upon others, it can still compete with others for food resources or living space. Figure 1.14j shows a community of various fish species living in close proximity.

Moving on, living things interact with the non–living components of their environment. The colorful tropical fish in Figure 1.14k are part of a coral reef *ecosystem*. An ecosystem is a system of living communities interacting with non-living parts of their environment. In order to survive, this ecosystem must remain within a very narrow temperature range (just around 80°F) and must be located at just the right depth so that it is always covered with water, yet close enough to the surface to receive sufficient sunlight. Water level and temperature are just two non-living factors that play roles in the survival of the species of this ecosystem. The fish pictured in Figure 1.14k, small organisms called *phytoplankton* (not visible to the naked eye and not evident in the picture), and *coral polyps* that secrete calcium carbonate are just a few of the numerous amazing creatures found in coral reefs. We are naturally awed and inspired by the beauty of ecosystems such as these, and we should embrace our human vocation of caring for the earth.

Finally, the *biosphere*, shown in Figure 1.14l, encompasses all living things on earth and is the largest level of biological organization we know of.

1.2.3 Living Things Metabolize

Living things undergo a process called *metabolism*, by which they use matter and energy to power all their processes. In order to remain alive, an organism must repeatedly take in matter from the environment. These molecules are then transformed into different molecules that the organism uses, harnessing energy in the process. Unusable matter is returned to the environment in the form of waste. Other organisms in the environment then transform the waste into usable building blocks, and the matter recycling process begins again.

Some types of organisms, such as plants, also have the amazing ability to make direct use of energy in the form of sunlight, storing that energy in the bonds of molecules. These molecules are then used by other organisms or broken down to retrieve the energy. All organisms need energy in some form to power all their processes. Without usable energy, they would cease living.

In essence, there are three major categories of organisms that participate in these metabolic processes, illustrated in Figure 1.15. *Producers*, such as moss, harness the sun's energy, storing it in molecules that can be eaten and used by other organisms. *Consumers*, such as the hedgehog, eat plants and other animals, reusing the matter and stored energy for their own purposes. Finally, *decomposers*, such as mushrooms, secrete special biomolecules that break down excreted waste products or the remains of dead organisms, allowing those molecules to be used again. In short, energy flows from the sun to producers, then to consumers, then to decomposers, and ultimately is dissipated as heat. The matter continues to be broken down and built back up again, recycled over and over. The cycling of matter and energy takes place in thousands upon thousands of metabolic reactions, which we discuss in much more detail in Chapter 4.

Figure 1.15. An example of a producer (moss), consumer (hedgehog), and decomposer (mushroom) in the same ecosystem.

Reflect for a moment on the exquisite design of this system. The interplay of producers, consumers, and decomposers shows the wisdom of our great God. Consider how God provides everything we need for life, and how wonderful it is that all His creatures support one another in their needs for matter and energy. Not only that, but He designed these processes in a sustainable way, such that the cycle continues on and on without ever being exhausted (at least so long as the sun continues to shine!). Let us thank Him for His goodness to us and resolve to care for the earth He designed for us so that we don't compromise this exquisitely designed environment through carelessness, waste, or pollution.

1.2.4 Living Things Grow, Develop, and Reproduce

Living things exhibit a pattern of growth over the course of their lifespan that leads toward reproduction. This does not simply mean that organisms get bigger—although attaining larger size is part of the process. Living things also develop into organisms of increasing complexity as time progresses. What is the purpose of this process? To reach sexual maturity and reproduce so that life may continue.

Let's look at the stages of human life as an example. The stages of fetal development are illustrated in Figure 1.16. A person begins as a single cell—the joining of a sperm and an egg with a unique genetic code. At that point, the cell begins to divide (a process called *mitosis*), becoming two cells, then four, then eight. As the process of cell division continues, the cells begin to grow and certain cells begin to specialize their roles. Though each cell has a complete copy

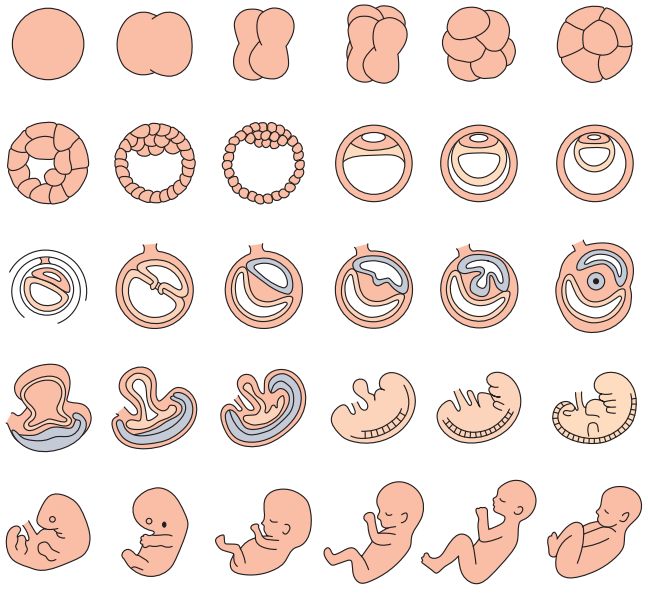


Figure 1.16. The stages of human fetal development.

of the person's DNA, specific cells begin using only certain parts of the DNA. As a result, some cells are set on a path to become blood cells, others are destined to become brain cells, and so on. As time progresses, the expressed genes in each cell begin to dictate how cells are arranged within the body. The growing baby begins to look more and more human-like, with a head, a face, a torso, two arms and two legs. The heart begins to beat just a few weeks after fertilization of the original egg, before the mother even knows she is pregnant!

Dramatic growth and differentiation of cells continues for about nine months, until the baby's lungs are ready to breathe oxygen, and then the baby is born. Yet even after birth, the process of growth and development continues.

The baby gradually gains the ability to roll over, crawl, walk, and talk. As the child reaches school age, she learns to read and write. She reaches physical milestones, such as losing baby teeth and gaining permanent ones. Eventually, the child reaches puberty, initiating a series of changes by which she becomes physically capable of sexual reproduction.

All the while, the person gains increasingly complex reasoning abilities. She can now visualize abstract concepts as she studies subjects in increasing depth throughout her high school career and beyond.

Development continues throughout adulthood as well. Around middle age, signs of aging appear—such as graying hair, diminishing eyesight, and menopause in women.

As you can see, human beings do not remain stagnant, but follow a predictable pattern of growth and development throughout life—from conception through death. This process includes becoming sexually mature so that one may reproduce, creating more individuals and continuing the human race.

All organisms go through some developmental process. Butterflies progress from caterpillars to adult butterflies; frogs change from eggs to tadpoles to adult frogs. Even bacteria pass through phases as they repeatedly go through the process of cell division. In summary, growth, development, and reproduction are processes pertaining to all life.

1.2.5 Living Things Use and Transmit Genetic Information

Before a building is built, an architect draws up the plans for the workers to follow. Before a play is performed, the actors require a script. Computers require software in order to perform any task.

In a similar way, an organism requires a set of instructions to control all its functions. However, rather than being drawn on a sheet of drafting paper or typed in word processing software, these instructions are encoded in a special language stored in the structure of a biomolecule called *deoxyribonucleic acid*, or *DNA*. Amazingly, the same genetic code is used by all life—from

the simplest bacteria to mammals and even to human beings. We delve into the fascinating details about DNA in Chapter 5. For now, we simply note the following four highly significant properties of DNA:

1. DNA can be copied in its entirety, so that the copies may be transmitted to offspring.
2. DNA can copy small portions of itself in order to give instructions to other parts of the cell.
3. The information in DNA is stored in chemical "language" composed of an alphabet of four compounds. We represent these compounds by four letters of the English alphabet. The chemical language is read and understood by other parts of the cell.
4. The language of DNA is the same for all living species on earth.

Each of the trillions of cells in your body contains instructions that are billions of DNA "letters" long. That's the amount of DNA required to encode for you! Though all living things share the same alphabet and the same language, no two species, nor even two individual humans, share the exact same genetic code. As a rough analogy, there are many novels written in English, but the sequence of letters in each novel is vastly different from the next. There are genres of similar novels, such as mystery, romance, historical fiction, and so on. These genres are analogous to the similar genetic codes shared by members of the same species. But because of the versatility inherent in a written language, no novel is identical to another. Consider the great care God has for us that He specifically designs each person with a unique genetic code. As Psalm 139:13–14 says, "For you formed my inward parts; you knitted me together in my mother's womb. I praise you, for I am fearfully and wonderfully made. Wonderful are your works; my soul knows it very well."

When living things reproduce, they pass their genetic code on to their offspring by one of two processes of reproduction—*asexual* or *sexual*. In asexual reproduction, a single-celled organism makes a copy of its DNA and then divides into two identical daughter cells. Thus, asexual reproduction results in genetically identical offspring. In sexual reproduction, two parents each contribute half their DNA to the resulting progeny. The result is a genetically unique individual.

To summarize, the DNA in all living things provides the foundational information used to determine how each life function is carried out. The DNA in every cell contains the instructions governing how the cell can behave. Living things transmit their DNA (in part or in whole) to the next generation, through either asexual or sexual reproduction.

1.2.6 Living Things Respond

As illustrated in the sad tale of the pet goldfish, living things respond. We use the word *stimulus* to indicate any event that evokes a reaction from an organism. The stimulus causes a signal to be transmitted in the form of light, sound, pressure, motion, temperature, or *chemical gradient* (a region of varying concentration in solution). An organism must have a sensory system in place in order to detect the stimulus, process the information, and then respond accordingly. The goldfish could sense the presence of the plastic plants in the aquarium and turn around and swim in the other direction.

To cite another example, say you are outside playing volleyball with your friends. Suddenly, the ball is rushing directly towards your head. You detect this stimulus by seeing the shadow of the ball passing in front of you, and you hear your friends yelling "heads up!" Your brain detects the information transmitted from your eyes and ears, interprets that information as an imminent threat, and immediately directs your muscles to respond. If you are like some of us, you might duck, cover your head, and move out of the way. Those who are more athletically inclined might instead jump towards the ball and spike it over the net. Either way, you sense a signal, process it, and respond.

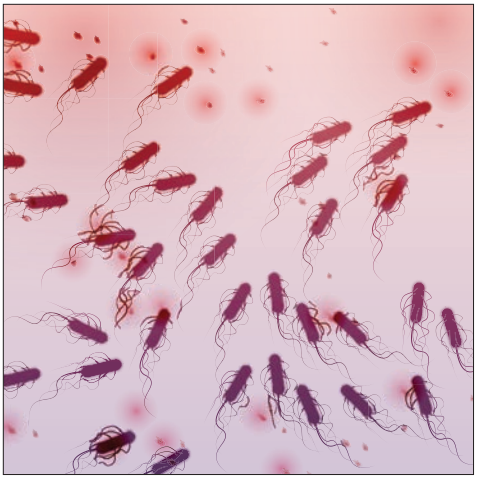


Figure 1.17. An artist's concept of bacterial chemotaxis in *E. coli*.

You might think that this property is only present in higher (more intelligent) organisms, but even simple bacteria are able to respond to stimuli. Many bacteria exhibit *chemotaxis*, the ability to sense concentrations of molecules and swim towards them (or away from them, if they are poisonous). This ability helps the bacteria both to find food and to avoid threats.

Figure 1.17 shows an artist's rendition of bacterial chemotaxis. The rod-shaped *E. coli* cells each have multiple *flagella* (singular: *flagellum*), string-like projections extending from their cell bodies. These flagella spin like propellers, enabling the bacteria to move. When no chemical attractants are present, the flagella all spin facing outward from the bacterium, and the bacterial cell tumbles in place. However, when an increasing concentration of a nutrient molecule is present (such as sugar), the bacteria align the flagella in the same direction. This alignment causes the bacteria to propel forward toward the sugar. Thus, bacteria respond to the stimulus of the chemical gradient caused by the sugar's presence and are rewarded with a tasty treat.

Though bacteria don't have a nervous system as you and I do, they can sense the presence of these molecules in the water and respond accordingly. Perhaps, then, it isn't really fair to consider *E. coli* a "simple" organism (though it is tiny and single-celled). The flagellum itself is a rather complex marvel of mechanical engineering. (I'll leave that one for you to look up yourself.) Life and its processes are truly amazing, no matter how large or small the organism.

Now, let's pause briefly to consider how stimulus and response relate to the notion of *homeostasis*. While organisms respond to stimuli in isolation, they also maintain various continuous stimulus/response processes so that the organism remains within life-sustaining limits.

To understand homeostasis, let's consider the thermostat on the heating/cooling unit of a house. The thermostat constantly monitors the temperature of the surrounding air, keeping it at a specified temperature. When I lived in the snowy state of Minnesota, I kept my thermostat set at 68 degrees Fahrenheit all winter long. If the temperature dropped below 68°F, the thermostat signaled the furnace to blast warm air until the temperature reading returned to the desired temperature. Now living in sunny California, I set my thermostat to 78°F during the summer. If the temperature should rise above this value, the thermostat signals the air conditioner to infuse cold air until the reading returns to 78°F. Rather than a one-time stimulus/response event, this is a continuously occurring stimulus/response feedback cycle.

In the same way, to maintain homeostasis organisms monitor pH, salt concentration, temperature, nutrient levels, and a whole host of other parameters—adjusting their responses to these conditions so that the body remains in an acceptable, life-sustaining range. Maintaining homeostasis is a particularly complex manifestation of the stimulus/response characteristic of life.

1.2.7 Living Things Adapt to the Environment

In a constantly changing environment, organisms must have strategies in place so they can survive, thus fulfilling their common purpose. One strategy is *adaptation*. In the present context, adaptation is not exhibited by an individual organism, but by a population of organisms

over several generations. This process of adaptation depends upon genetic variability among the members of the population.

As an example, consider the finches that Darwin observed during his voyage to the Galapagos Islands in 1845, illustrated in Figure 1.18. Since the Galapagos Archipelago originated from volcanic activity, its species had to migrate there from other locations. These finches probably came from a population of birds on the mainland. As the finches settled on the different islands of the archipelago, differing food sources led to higher reproductive success for birds with certain traits. For example, in Figure 1.18, the large ground finch labeled #1 (*Geospiza magnirostris*) has a large, short beak that is adapted to cracking nuts. Isolated on an island with nuts as the major food source, birds in the original population that had this trait already (by the nature of genetic variability) were more successful in obtaining food. Better fed, birds with the large, short beak were also more successful at reproduction. After several generations, this trait became predominant in the population, due to the survival advantage it conferred.

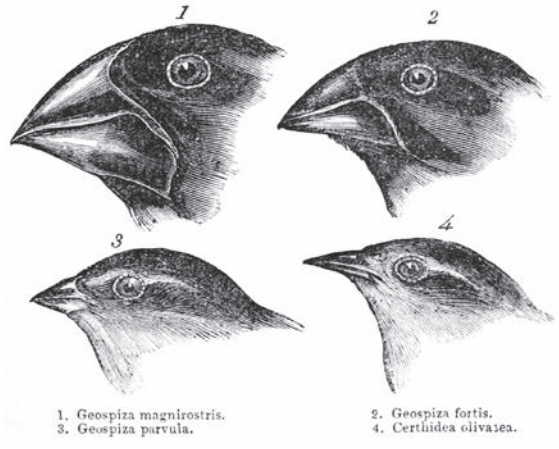


Figure 1.18. Finches of the Galapagos Islands, with beaks adapted to varying food sources.

On the other hand, the medium ground finch #2 (*Geospiza fortis*) lived on an island with small soft seeds as its major food source. As a result, finches with the beak most adept at eating these seeds had a reproductive advantage. After several generations, most of the medium ground finches in the population possessed a beak like the one pictured here (drawn in 1845). Interestingly, since that time, scientists observed that a drought in the 1970s caused further adaptation in this population. The drought shifted the major food source from small soft seeds to much harder seeds, and as a result, scientists observed a 10% change in the sizes of the beaks of the medium ground finch. This adaptation to changes in climate enabled the birds to utilize the changing food source more effectively.

Adaptation can also be readily observed in bacterial populations. In 1943, penicillin was introduced as an effective antibiotic against a disease-causing bacterial species, *Staphylococcus aureus* (*S. aureus*). After just two years, up to 20% of *S. aureus* infections became resistant to penicillin treatment. These resistant strains of *S. aureus* had adapted to the threat (by taking in more of an enzyme called *penicillinase*, which breaks down the deadly antibiotic). Later, another antibiotic called *methicillin* was introduced as an effective treatment. Yet today, MRSA (methicillin-resistant *Staphylococcus aureus*) infections are a formidable problem in medicine. As new antibiotic treatments are introduced, bacterial populations develop resistance to antibiotics and are not so easily killed off. This is why it is important to use antibiotics cautiously. We want to avoid generating antibiotic-resistant strains we cannot treat.

Adaptation is an important feature of life that enables populations to survive amid changing conditions. We explore the process of adaptation (also called microevolution) further in Chapter 12.

1.3 The History of Biogenic Theory (Can life emerge from non-life?)

So far, we have explored the answers to two questions: 1) By what methods do we make new discoveries in the field of biology? 2) By what criteria do we judge something to be alive? We now use this information to explore how ideas about biology have changed over time.

1.3.1 Aristotle and Redi

The ancient Greek philosopher Aristotle (Figure 1.19) wrote extensively about nature (natural philosophy). Aristotle was the first philosopher to propose the theory of *spontaneous generation*. Spontaneous generation is the idea that living things can arise randomly out of non-living matter. To Aristotle, spontaneous generation made sense according to everyday observation. Frogs were seen to emerge from the mud alongside riverbeds—therefore, frogs must be made out of the mud. Worms are seen on rotting meat—therefore, worms must come directly from that meat.

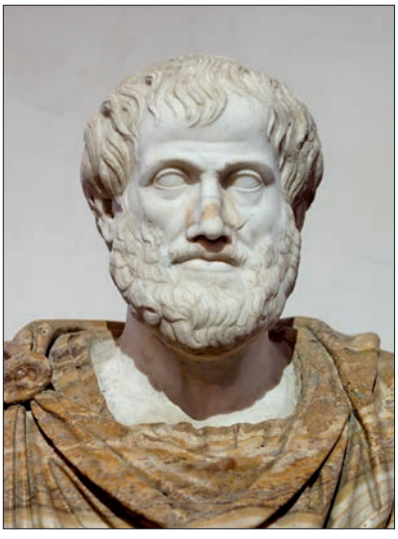


Figure 1.19. A statue of ancient Greek philosopher Aristotle (384–322 BC).

Spontaneous generation was not seriously questioned for about 2,000 years. Then, in 1668, Tuscan naturalist Francesco Redi (Figure 1.20) performed an experiment showing that maggots found on rotting meat did not actually originate from the decaying flesh. Redi assembled a large array of different types of meat, leaving some samples to rot in uncovered jars, and others in jars covered with cheesecloth. The uncovered samples became infested with maggots after a few days. However, the covered samples had no maggots directly on the meat. Instead, adult flies were seen hovering over the cheesecloth, where they laid their eggs. Redi concluded that maggots are simply part of the life cycle of flies, and that an adult fly must lay its eggs on the rotting meat in order for the maggots to develop there. Redi thus showed that life does not proceed directly from decaying matter, as the proponents of the theory of spontaneous generation argued. Rather, life proceeds from parent to offspring. Redi's famous conclusion in Latin was *omne vivum ex vivo*, or *all life comes from life*.

Figure 1.20. Tuscan naturalist Francesco Redi (1626–1697).

1.3.2 Needham and Spallanzani

Eighty years passed before another test of the theory of spontaneous generation occurred. While Aristotle and Redi could only observe the generation of *macroscopic* animals, by the 18th century the invention of the microscope allowed investigation of *microorganisms* as well. In 1748, Irish priest John Turberville Needham (Figure 1.21), in collaboration with French aristocrat Comte de Buffon, performed an experiment that supported the theory of spontaneous generation. Needham heated mutton gravy in stoppered glass tubes until boiling, under the assumption that boiling killed all life within. Afterwards, Needham was able to observe many quickly-moving microorganisms and smaller so-called "organic molecules" in the fluid. According to Needham's theory supporting spontaneous generation, these "organic molecules" had a special life-giving force and clumped together to form larger microorganisms called "animalcules." Thus, he concluded that the microorganisms arose spontaneously from previously non-living matter.

Figure 1.21. Irish priest John Turberville Needham (1713–1781).

In 1765, Italian priest Lazzaro Spallanzani (Figure 1.22) questioned the results of Needham and Buffon, repeating their experiment with some modifications. First, Spallanzani hermetically sealed his tubes, meaning that he melted the glass to make an airtight seal. Second, he boiled the gravy for at least an hour. As a result, Spallanzani did not observe any microorganisms forming after treatment. Since they were contemporaries, Spallanzani's results stirred up a debate between Needham and himself. Spallanzani argued that Needham did not boil his gravy long enough to kill all the organisms, and that by not tightly sealing his vessels airborne microorganisms could cause contamination. Needham responded that Spallanzani's tight seal and excessive boiling destroyed the "life force" in the air that is necessary to generate new life.

Applying what we know about the Cycle of Scientific Enterprise, we see how both Needham and Spallanzani were attempting to use competing theories to account for the same body of facts. According to the theory of spontaneous generation, Needham could predict (make a hypothesis) that new life would emerge after all previous life had been killed. He performed an experiment that seemed to support this hypothesis, and so evidence for spontaneous generation was strengthened. Spallanzani, suspecting that all facts did not, in reality, support the theory of spontaneous generation, proposed instead that Needham's results were the result of experimental flaws. Spallanzani repeated Needham's experiment with improved design, achieving the opposite result—no microbial growth. Throughout the history of science, conflicting results and even fierce debates have been common. These debates cause the Cycle of Scientific Enterprise to move forward toward ever stronger theories, as experimental flaws and other hidden mysteries are revealed by further testing. Scientists might not be as motivated toward repeated testing and improved experimental design if everyone agreed all the time.

Figure 1.22. Italian scientist Lazzaro Spallanzani (1729–1799).

1.3.3 Pasteur and the Victorian Debates

A century passed, and the question of spontaneous generation was still far from settled. In the 1860s, French scientist Louis Pasteur (Figure 1.23) designed an experiment to settle this question as part of a contest hosted by the French Academy of Sciences. Needham's criticism of Spallanzani's experiment was that it excluded outside air, thus impairing some "vital force" from forming new life. As a result, Pasteur designed a new kind of flask that would allow air inside, but not heavy dust particles. This apparatus, known as the "swan-necked flask," is shown in Figure 1.24. Pasteur predicted that contamination from the outside air was the cause of bacterial growth after boiling a broth or gravy, and his swan-necked flask was designed to prevent this contamination.

Figure 1.23. French scientist Louis Pasteur (1822–1895).

First, Pasteur boiled broth in several of his special flasks. In the first sample, he broke off the neck of the flask, exposing the broth to the air above. This sample grew microorganisms after a few days. In the next sample, he simply boiled the broth, and allowed it to sit for months. Even though it was exposed to the air through the open swan-necked flask, no bacterial growth occurred. After many months, Pasteur finally tipped the flask over, exposing the broth to the dust that had settled at the edge of the opening, and then setting it upright again. After a few days, bacterial growth occurred. Pasteur's experiment gave strong support to *biogenic theory (biogenesis)*—all life comes from previously existing life.

Though many synopses on the history of spontaneous generation end with Pasteur, it should be noted that the debate raged on for at least another decade. English scientist Thomas Henry Huxley (Figure 1.25) popularized Pasteur's results, while another English scientist named Henry Charlton Bastian (Figure 1.26) fervently debated Huxley in favor of spontaneous generation. Bastian, a supporter of Darwin's newly published theory of evolution, theorized that the first life must have emerged from non-life, and that microorganisms continue to do so. Rather than use the term spontaneous generation, Bastian instead coined the term *archebiosis*. This word implies that life, while emerging from nonliving matter, does so according to natural law. Previous supporters of spontaneous generation viewed the process as completely random and coincidental, not necessarily following any natural laws.

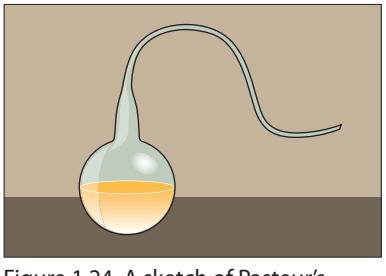


Figure 1.24. A sketch of Pasteur's swan-necked flask.

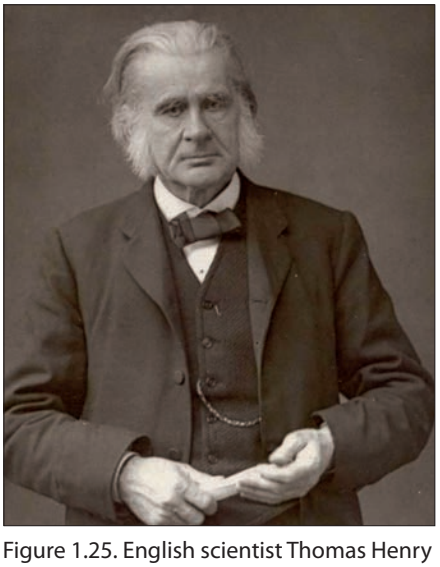


Figure 1.25. English scientist Thomas Henry Huxley (1825–1895).

In the midst of these debates between Huxley and Bastian, Irish physicist John Tyndall (Figure 1.27) entered the fray. Tyndall's early experiments heating "infusions" in an enclosed dust-free environment showed no microbial growth. However, after some time in repeating these experiments, Tyndall did begin to notice bacteria forming after heating in the dust-free air. He eventually traced these unexpected results to a bale of hay that he recently had moved into the room. Repeating his experiments in a different building yielded the original results—no bacterial growth. A subsequent discovery by another scientist, Ferdinand Cohn, showed that hay produces an interesting phenomenon. Bacteria that live in hay are notorious for forming heat-resistant spores that can survive excessive boiling. These spores from the hay contaminated Tyndall's experiments that showed bacterial growth, which explains why moving his experiment to another

Hmm... Interesting. *Comparing Orders of Magnitude*

The study of biology can be an overwhelming prospect because there are so many facts to learn. To illustrate, let's look at some mathematical comparisons relevant to biology.

Say you live to be 100 years old. Doing some simple math, the span of your life would be:

$$100\ \text{yr} \cdot \frac{365\ \text{dy}}{\text{yr}} = 36{,}500\ \text{dy}\ (\simeq 10^4\ \text{dy})$$

$$36{,}500\ \text{dy} \cdot \frac{24\ \text{hr}}{\text{dy}} = 876{,}000\ \text{hr}\ (\simeq 10^6\ \text{hr})$$

$$876{,}000\ \text{hr} \cdot \frac{60\ \text{min}}{\text{hr}} = 52{,}560{,}000\ \text{min}\ (\simeq 10^8\ \text{min})$$

$$52{,}560{,}000\ \text{min} \cdot \frac{60\ \text{s}}{\text{min}} = 3{,}153{,}600{,}000\ \text{s}\ (\simeq 10^9\ \text{s})$$

So, if you live to be 100, you will have lived about three billion seconds. By comparison, your body has about 3.7×10^{13} cells and a similar number of bacterial cells that live inside your gut. Of your cells, your brain contains about 100 billion (10^{11}) neurons, each of which can make 1,000 connections for a capacity of 10^{14} overall connections.

The number of cells in your body far exceeds the number of seconds in your lifespan, so there is no way you could ever catalog them all. Yet, our heavenly Father, who created all life on earth, knows the number of hairs on your head (Matthew10:30) and the number of cells in your body. God also intimately knows every base pair of the DNA (numbering about 3.2 billion) in each of your cells and how that information makes you uniquely you.

Taking our investigation a step further, it has been estimated that in all human history about 175 million books have been written. With only about 53 million minutes in your lifespan, you have no hope of reading them all (as if you wanted to). Some say that all these books could be preserved digitally in about 175 terabytes of data. (Tera is the SI prefix that represents 10^{12}, so 175 terabytes is about 10^{14} bytes). Furthermore, current estimates of the amount of information contained on the Internet fall in the zettabyte range (or 10^{21} pieces of data). These numbers regarding books written and information on the Internet represent a fair fraction of the sum of information that humanity has collectively produced over time.

By contrast, it has been estimated that the total of all DNA base pairs contained in the biosphere, or in every living thing on earth, numbers around 5×10^{37} base pairs. Thus, the number of base pairs contained in all life is about 10^{16} (10 quadrillion) times larger than the sum total of all information contained in books and on the Internet.

Let that sink in for a minute. How much greater is God's knowledge and power than our own—that the blueprint for life exceeds the sum total of human accomplishment by 16 orders of magnitude! No wonder the study of biology can be overwhelming. There is no way we can understand the intricacies of life the way God does.

On the other hand, God didn't design our world in a random or chaotic way, but infused the created world with order and beauty. Not only that, but God endowed humanity with the ability to understand, question, and explore the world. Biology is unified by general logical principles that we can begin to understand. And as we do, we experience ever greater awe toward the One who designed it all.

Figure 1.26. English physiologist Henry Charlton Bastian (1837–1915).

building solved the problem. Tyndall then invented a procedure for killing the spores—by intermittent and repeated boiling and cooling. It seemed that the debates over spontaneous generation were definitively put to rest, as nearly everyone then accepted that life arises only from previously existing life.

1.27. Irish physicist John Tyndall (1820–1893).

1.3.4 Modern Vocabulary

To summarize this section, throughout history scientists (and the public at large) have taken different stances on the question of spontaneous generation. Aristotle and Redi focused on the generation of macroscopic life, arguing for and against its emergence from non-living matter. Needham and Spallanzani focused on the question of microorganisms, and whether they can arise from a broth that has been heat-sterilized. Pasteur and his contemporaries in the 1860s focused on the experimental complications of previous work, correcting for contamination by airborne microorganisms and heat-resistant bacterial spores. Additionally, they engaged in a fierce public debate over the theory of biogenesis. By the end of this era, the theory that life must proceed from life (biogenesis) became nearly universally accepted.

Today, scientists sometimes use the term *abiogenesis* rather than spontaneous generation or archebiosis. Huxley coined this term, where *a–* is a prefix meaning "not," *bio–* means "life," and *–genesis* means "beginning." The term abiogenesis implies an event that may have occurred just once in the past, resulting in the first cellular life. This idea is controversial; however, it is important that you understand the distinctions between the three terms: spontaneous generation (life emerges randomly from non-living matter on a regular basis); archebiosis (life emerges from non-living matter on a regular basis according to natural law); and abiogenesis (life may have emerged from non-life just once a long time ago; since that time, life has proceeded from other life).

The origin of life is a subject that is still actively being researched today. We now know just how complex a single cell is, and it is not easy to discern exactly how its individual components could have come together in just the right way to form a living—and self-replicating—entity from a non-living one. However, just as everything in nature follows orderly, beautiful, mathematical principles designed by the Creator Himself, we can trust that God's creative work is ultimately responsible for all living things, past, present, and future. As the apostle Paul writes in Colossians 1:17, "He is before all things, and in Him all things hold together." Maybe you will one day participate in the Cycle of Scientific Enterprise yourself, perhaps even making your own contribution to the theory of biogenesis.

Chapter 1 Exercises

SECTION 1.1

1. Distinguish between truth and facts.
2. Write three true statements and three factual statements (that are correct so far as we know.)
3. Distinguish between theories, hypotheses, and experiments.
4. Explain how the Cycle of Scientific Enterprise works.
5. Make a table listing the three types of microscopes discussed in this chapter. For each, include columns with the following information: 1) how the image is obtained, 2) range of magnification, 3) degree of resolution, 4) types of structures that can be observed, and 5) description of the resulting image.
6. For each of the seven common measurements/metric prefixes listed in Table 1.1, identify two additional applications to actual objects or phenomena in nature.
7. Compare the micron and the angstrom (i.e., calculate their ratio).

SECTION 1.2

8. List and briefly describe the six characteristics of life.
9. Make a table listing the levels of biological organization. For each level, list a defining characteristic.
10. Explain why a cell is the simplest level of organization considered to be alive.
11. Other than those discussed in the book, give an example of a cell type, tissue, organ, and organism. Make sure that each example is a component of the level of organization above it.
12. Write a paragraph distinguishing between producers, consumers, and decomposers.
13. Compare and contrast sexual and asexual reproduction.
14. Briefly trace the developmental process of a human being, from conception through death.
15. Besides those mentioned in the book, think of three examples of an organism responding to a stimulus. For each example, explain what the stimulus is, how the organism senses it, and how the organism appropriately responds.
16. Define homeostasis, giving an example of an organism exhibiting homeostasis.
17. Define adaptation, giving an example of a population adapting to changing environmental conditions.

SECTION 1.3

18. Compare and contrast the theories of Aristotle and Redi.
19. Compare and contrast the experiments of Needham and Spallanzani. How were their theories different from those of Aristotle and Redi?
20. Describe the experiments and conclusions of Louis Pasteur.
21. What experimental modifications did John Tyndall make, and how did his results strengthen biogenic theory?
22. Distinguish between Bastian's term archebiosis and Huxley's term abiogenesis. How are these two terms different from the term spontaneous generation?

diated series of many chemical reactions. Collectively, these comprise cellular respiration. Many of these are redox reactions (Section 4.1.2).

Before cellular respiration can take place, your body must transport fuel and oxygen to each cell. The food you eat is broken down (digested) in the stomach by a number of hydrolytic enzymes. The resulting small molecules are absorbed through the small intestine into the bloodstream, which delivers them to the cells. Though many molecules can serve as fuel sources (lipids, proteins, and carbohydrates), we focus on glucose here for simplicity. Broken down products of the other types of molecules can all enter into cellular respiration at one point or another.

When you breathe in oxygen gas, it diffuses across your lungs into the red blood cells in your bloodstream, where the *hemoglobin* protein transports it to every cell. The small nature of the O_2 molecule allows its passage across membranes by simple diffusion, both in the lungs and at the receiving cells. Once the cells have glucose and O_2 molecules at hand, cellular respiration can commence.

At this point, it would be helpful for you to review the content of Sections 3.1.3 and 3.2.3. Since different stages of cellular respiration occur in different cellular locations (including the cytosol and the mitochondria), make sure you have refreshed your memory as to the properties of these parts of the cell.

4.2.2 The Four Major Stages in the Cellular Respiration Process

The overall purpose of cellular respiration is to turn food and oxygen into usable energy. This process, illustrated in Figure 4.7, is tightly controlled and occurs in four identifiable stages:

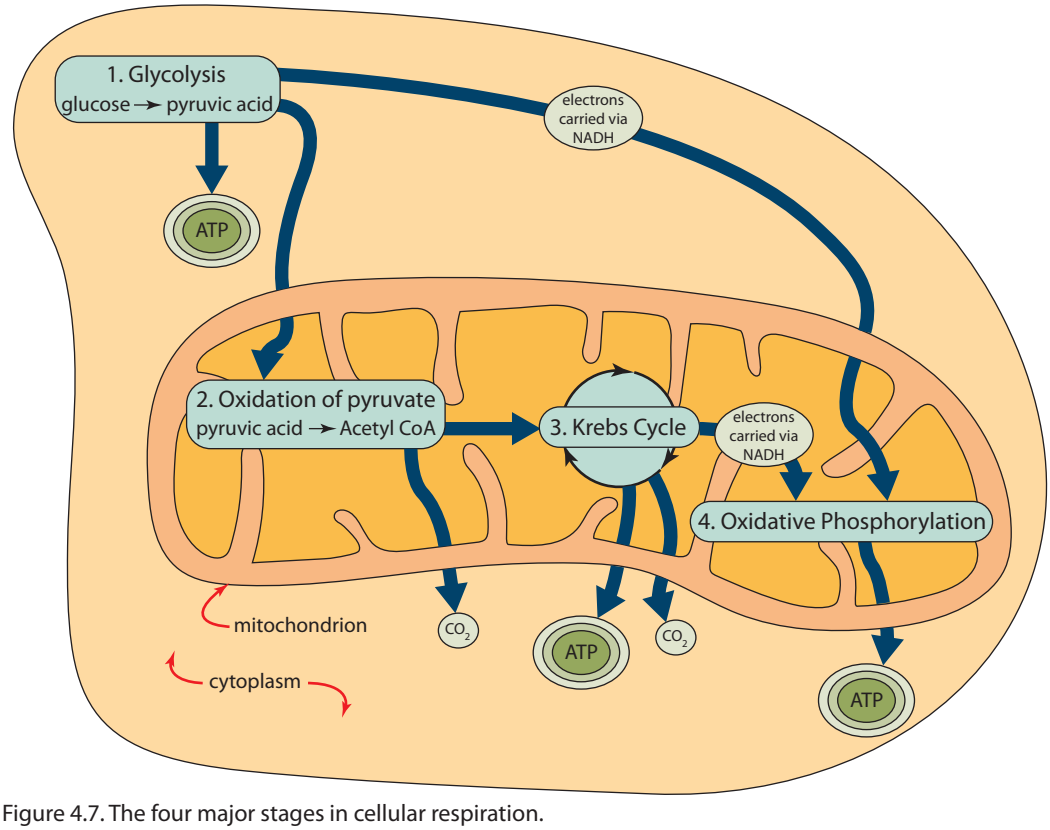


Figure 4.7. The four major stages in cellular respiration.

1. *Glycolysis* Literally meaning "sugar breaking," glycolysis occurs in the cytosol. This stage breaks 6-carbon glucose molecules into two 3-carbon pyruvic acid molecules,[1] while also releasing a small amount of ATP and high-energy electrons for future use, carried by the electron carrier molecule NADH.
2. *Oxidation of pyruvate* After moving into the mitochondrial matrix, the pyruvic acid (or pyruvate) is converted into a 2-carbon compound called Acetyl coenzyme A (Acetyl CoA). A *coenzyme* is one of a class of molecules called *cofactors*—molecules that must be present in addition to a specific enzyme in order to catalyze a particular reaction.
3. *Krebs cycle* Taking place in the mitochondria, this cycle takes Acetyl CoA and transforms it into various other 4-, 5-, and 6-carbon compounds, releasing NADH and some ATP in the process. Carbon dioxide is released as a byproduct. (The waste CO_2 is transported to the lungs and exhaled.) This process is also called the *citric acid cycle* or the *tricarboxylic acid* (*TCA*) *cycle*.
4. *Oxidative Phosphorylation* This process takes place in the mitochondrial matrix. Using the energy of electrons stored in carrier molecules such as NADH, an *electron transport chain* (ETC) drives a molecular motor called the *ATP synthase*. This amazing molecule "charges" used-up ADP molecules, converting them back into ATP that the cell can use. This process cannot proceed without oxygen, which serves as the final electron acceptor.

If reading those paragraphs makes your head spin, don't worry. We now walk through the process in detail, elaborating on each step. As you grapple with understanding this topic, think about each of these reactions occurring in every one of your cells. The air you breathe and the food you eat are powering the amazingly complex mitochondrial machinery, yet God knows every molecule and every enzyme and what they are doing in each of your cells, every nanosecond of your life. This process is so essential that if a person's oxygen supply is cut off for just a few minutes, the person dies. As you study this complex topic, let it be an opportunity to worship

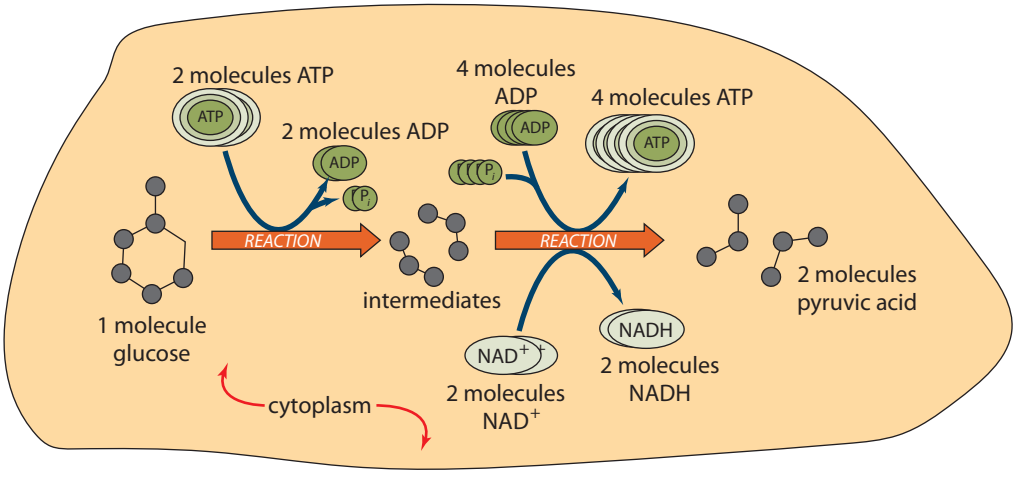


Figure 4.8. Schematic representation of the reactions in the glycolysis process. In the glucose, intermediate, and pyruvic acid molecules, only the carbon atoms are shown (in gray).

1 Note that pyruvic acid ($CH_3COCOOH$) also exists in its ionized form, called pyruvate (CH_3COCOO^-). These two entities exist in a dynamic mixture, depending on the pH of the environment. We use the two terms interchangeably in this text.

our great God who knows you in far greater detail than this relatively simple overview can hope to communicate.

1. Glycolysis

Figure 4.8 is a schematic illustration of the glycolysis reaction pathway, starting with the 6-carbon sugar glucose. This figure is a simplified representation of a complex series of chemical reactions—each one catalyzed by a specific enzyme. Glycolysis occurs in the cell cytoplasm and converts glucose into pyruvic acid, the compound that enters the mitochondrion.

The first half of glycolysis is called the *energy investment phase*, using two ATP molecules to proceed. These ATPs are hydrolyzed to ADP (as Figure 4.2 illustrates), resulting in two 3-carbon intermediates.

In the second, *energy payoff phase* of glycolysis, these 3-carbon intermediates are transformed into different 3-carbon intermediates—pyruvic acid—with the net loss of high-energy electrons. These electrons are transferred to the carrier molecule NAD^+, forming the reduced molecule NADH, with a net production of two NADH molecules per glucose molecule. Additionally, four ATP molecules are generated. Because two ATP molecules are invested in the first phase of glycolysis and four are produced in the second phase, there is a net gain of two ATP molecules per glucose that are immediately available to serve the energy needs of the cell.

We note in passing that the glycolysis process does not require oxygen, and can thus occur in energy processes where there is no oxygen. One of these is fermentation, which we consider later.

The process of glycolysis may be summarized as follows:

1. Converts one glucose molecule into two pyruvic acid molecules.
2. Uses two ATP molecules and generates four ATP molecules, a net production of two ATPs.
3. Generates two NADH molecules (electron transporters).
4. Occurs in the cytoplasm of cells.
5. Proceeds in the absence of oxygen.

2. Oxidation of Pyruvate

In the next step, two molecules of pyruvic acid each react with a cofactor molecule called coenzyme A (CoA), as illustrated in Figure 4.9. The products of this reaction are Acetyl-CoA, NADH, and carbon dioxide. As mentioned above, a cofactor is a molecule that must be present in addition to a specific enzyme in order to catalyze a particular reaction. This type of molecule is

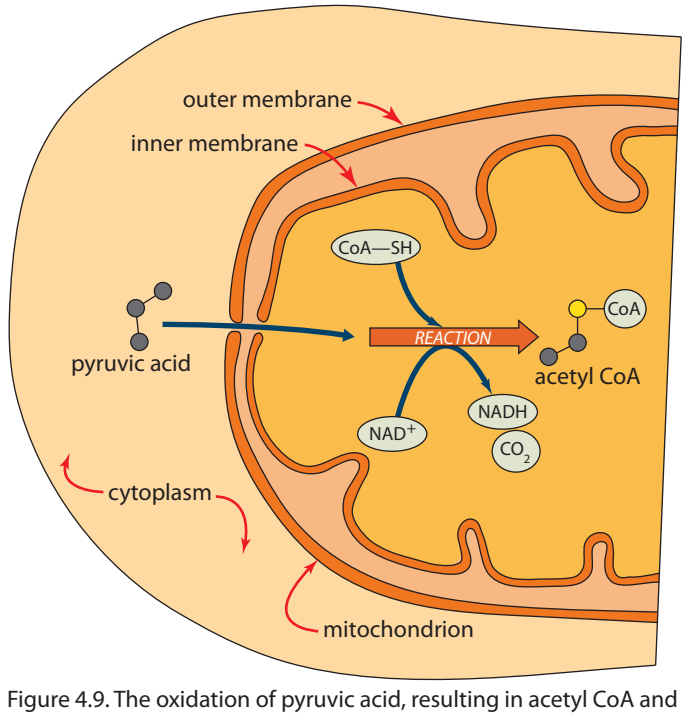


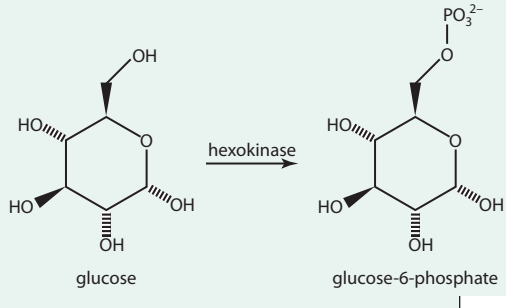
Figure 4.9. The oxidation of pyruvic acid, resulting in acetyl CoA and generating NADH and CO_2 in the process. Again, only carbon atoms are shown in the representations of the molecules, except for the yellow sulfur atom shown in the acetyl CoA product.

Hmm... Interesting. The Energy Released by ATP Hydrolysis

When we say that the hydrolysis of ATP releases energy that powers cells, you may wonder how this works. What form is that energy in? And how is it used to power processes in the cell?

When ATP is hydrolyzed into ADP and P_i, the P_i is rarely ever just released by itself. Instead, the P_i is almost always transferred to another molecule, activating it for another chemical reaction. An organism's metabolism is a series of interconnected, step-wise chemical reactions, one after the other. For example, the glycolysis process shown as two reactions in Figure 4.7 actually consists of a series of at least 10 intermediate steps. A small bit of energy is released as heat at each step, but most of the energy is converted into chemical potential energy of the next molecule in the series.

The very first step in the glycolysis series, catalyzed by hexokinase (mentioned in Figure 4.4), converts glucose to a molecule called glucose-6-phosphate, as the figure below shows. This reaction, called phosphorylation, pulls a phosphate group from ATP and attaches it to the glucose to yield glucose-6-phosphate. The glucose-6-phosphate now has more chemical potential energy than the glucose did, and can successfully undergo the next several reactions in the glycolysis pathway. A few steps later, another phosphorylation reaction occurs using another molecule of ATP.



glucose glucose-6-phosphate

All metabolic reactions are just manifestations of the law of conservation of energy. The ATP molecule is like a roller coaster at the top of a hill, with high gravitational potential energy. Successive chemical reactions represent lower hills on the up-and-down pattern that roller coasters often take, only energy is being transferred into chemical potential energy of different molecules instead of gravitational potential energy of different hills. At each step, little bits of energy are lost to heat, just as little bits of energy on roller coaster are lost to friction. When the roller coaster needs to go up an especially large hill, an additional source of energy (such as a motor with a chain) is required to supply the needed gravitational potential energy. Likewise, an ATP molecule supplies the energy via a phosphorylation reaction when the chemical reaction needs an energy boost.

And what about the heat? The heat lost from metabolism helps maintain body temperature and is eventually released from the body as infrared electromagnetic radiation. This is how snakes sense rats in the dark and is why we can see other people in the dark via night vision goggles.

Another illustration of the way the energy from ATP hydrolysis is used is in the sodium-potassium pump (Figure 3.46). The pump is a protein embedded in the cell membrane. In its normal configuration, the protein allows sodium ions in the cell to enter the channel. When a passing ATP molecule phosphorylates a molecule in the protein, the protein's structure becomes unstable and the protein changes its shape to regain stability, ejecting the sodium ions outside the cell and allowing potassium ions outside the cell to enter the channel. When the phosphate group is removed from the protein, which happens spontaneously, the protein's structure again becomes unstable and it changes back to its original shape, opening to the inside of the cell and releasing potassium ions inside the cell.

Amazing? I should say so.

called a coenzyme because, like an enzyme, it is not itself consumed in the chemical pathway and can therefore be reused. However, it is not composed of protein as enzymes are.

In this reaction, the pyruvic acid molecules are first ionized to form pyruvate ions. Then the CoA (containing sulfur and hydrogen atoms) attaches to the pyruvate to form acetyl-CoA. Notice that pyruvic acid contains 3 carbons, and the acetyl group in acetyl CoA only contains 2 carbons. The remaining carbon is released as CO_2. Because this process is a redox reaction, electrons are transferred to NAD^+ to form NADH.

Recall that glycolysis yields two pyruvic acid molecules per glucose. This means the oxidation of pyruvate generates two NADH molecules and two CO_2 molecules per glucose.

The major product of this reaction, acetyl-CoA, then feeds into the next step of cellular respiration—the Krebs cycle.

3. Krebs Cycle

Figure 4.10. Hungarian biochemist Albert Szent-Györgyi (1893–1986).

The Krebs cycle is a wonder of biochemistry with an interesting history. Preliminary components of the pathway were discovered by Hungarian biochemist Albert Szent-Györgyi (Figure 4.10), for which he received the Nobel Prize in 1937. The entire pathway was elucidated by German biochemist Hans Adolf Krebs (Figure 4.11) in 1937. He won the 1953 Nobel Prize for this important discovery.

Interestingly, both men were affected by their status as Jews in Germany. Earlier in his career, Krebs earned repute for his groundbreaking work in the discovery of other metabolic pathways. Despite his accomplishments, he was forced to flee Germany in 1933 because of his Jewish heritage. Recognizing his talent, the University of Cambridge in England quickly recruited him, allowing his research to continue.

During WWII, Szent-Györgyi joined the Hungarian resistance movement, helping his Jewish friends escape from the Axis-aligned country. In 1944, he went to Cairo under the guise of a scientific lecture, but actually was there to collaborate with the Allies. As a result, Adolf Hitler himself issued a warrant for Szent-Györgyi's arrest. He became a fugitive, eventually emigrating to the United States.

Figure 4.11. German biochemist Hans Adolf Krebs (1900–1981).

Let's turn now to describing the Krebs cycle. In order to be energetically favorable, the Krebs cycle proceeds in a continuous, cyclic fashion (as cycles do), with carbon-containing CO_2 molecules leaving the cycle at various points. The cycle is repeated twice for each molecule of glucose that undergoes glycolysis.

Each turn through the cycle begins with the reception of an Acetyl CoA molecule from the pyruvate oxidation. Immediately, the large CoA coenzyme activates a molecule of oxaloacetate to produce citrate (the molecule giving rise to the name citric acid cycle). The CoA then leaves the cycle and becomes available to oxidize another molecule of pyruvic acid.

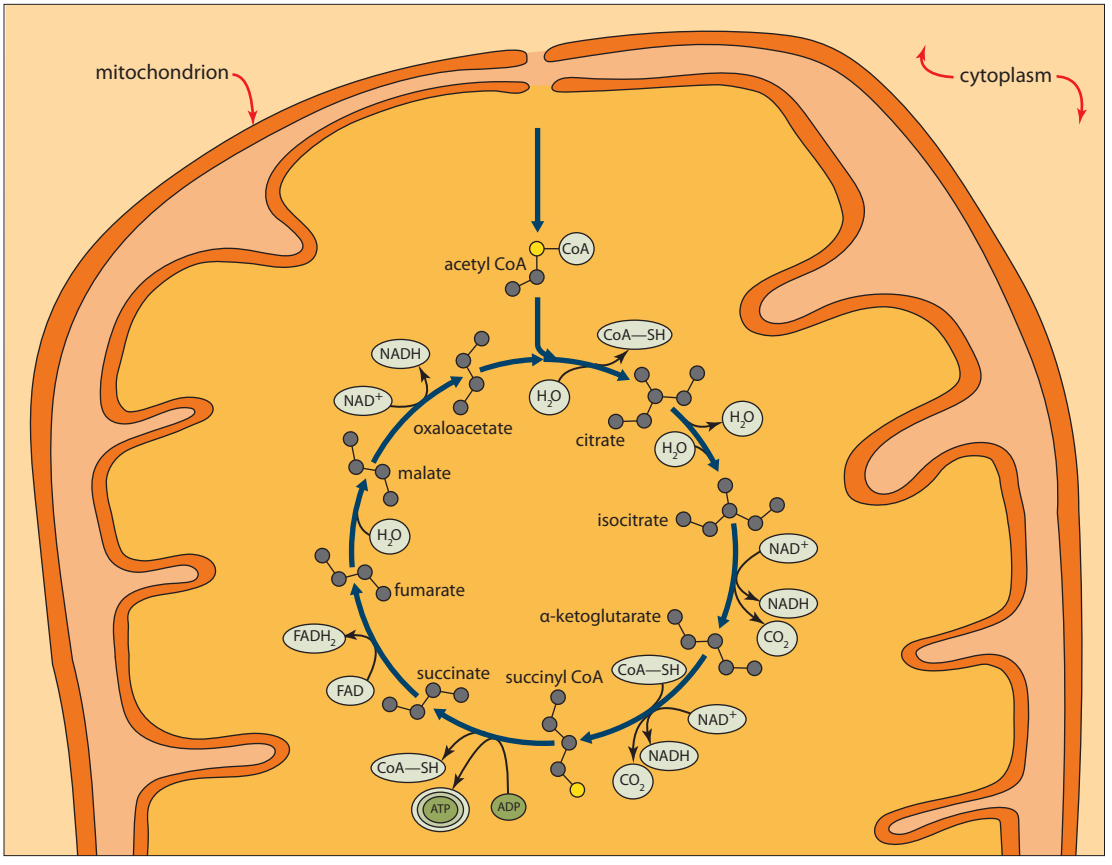


Figure 4.12. The Krebs cycle. Each step is catalyzed by an enzyme, and many intermediates may be fed into this cycle by other metabolic pathways beyond the scope of this course. This stage of cellular respiration is cyclical, repeating twice before a particular glucose molecule is completely broken down into carbon dioxide.

Studying Figure 4.12, you see that eight distinct molecules appear at the various stages of the cycle. The diagram is drawn to indicate the number of carbon atoms present in each molecule, and you can observe when carbon atoms enter the cycle (at the top) or leave (in the form of CO_2). The CO_2 molecules return to the blood to be exhaled or to regulate pH in the bicarbonate buffer system in the blood. Each time a CO_2 molecule leaves the cycle, the resulting organic molecule is one carbon shorter. Thus, the organic molecules vary from 6-carbon to 4-carbon.

As the cycle proceeds, several high-energy electron carriers are produced—both NADH and its slightly less-energetic cousin, $FADH_2$. These molecules transport electrons to the electron transport chain in the next phase of cellular respiration.

At the bottom of Figure 4.12, you see that an ATP molecule is produced in addition to the high-energy electron carriers. Thus two ATPs are produced per glucose molecule, since the cycle turns twice per glucose. The ATP becomes immediately available for the cell's energy needs.

The Krebs cycle may be summarized as follows:

1. Repeats twice per glucose that enters glycolysis.
2. The double-cycle input molecules are two Acetyl CoA molecules per glucose.
3. The double-cycle outputs are two ATPs, six NADH, two $FADH_2$, and four CO_2.
4. Occurs in the mitochondrial matrix.

5. Produces the ATP used for the cell's energy needs. The NADH and $FADH_2$ enter the electron transport chain and the CO_2 is exhaled from the body.

4. Oxidative Phosphorylation

So far, we have walked through glycolysis, the oxidation of pyruvate, and the Krebs cycle in detail. For each glucose molecule, we have broken down the 6-carbon glucose molecule into carbon dioxide, generated a net of four ATP molecules, and stored high-energy electrons in ten NADH carrier molecules and two $FADH_2$ carrier molecules (two electrons per carrier molecule). In the final stage of cellular respiration, there is a large payoff in terms of additional ATP molecules.

The purpose of oxidative phosphorylation is to use the energy contained in NADH and $FADH_2$ to overcome the high energy cost involved in the chemical reaction that produces ATP, Equation (4.1):

$$\text{ADP} + \text{phosphate} \rightarrow \text{ATP} + H_2O$$

The result is ATP that the cell can use for every process.

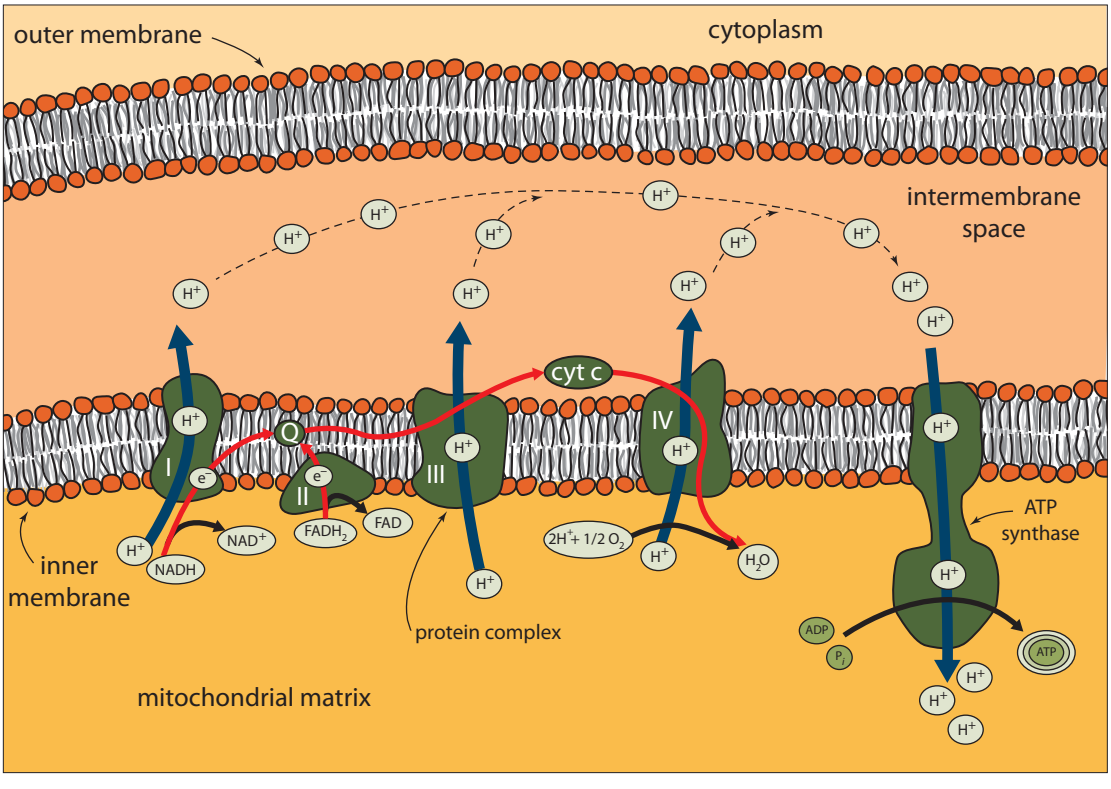


Figure 4.13. Oxidative phosphorylation. Multi-enzyme complexes I, II, III and IV comprise the electron transport chain. Using the electron carriers (NADH and $FADH_2$) from previous steps, these membrane proteins pass electrons from one protein to the next, releasing a controlled amount of energy at each step that drives the active transport of H^+ ions across the membrane. The final electron acceptor is O_2, producing water as the final product. The rightmost enzyme is the ATP synthase, powered by the passive transport of H^+ back into the mitochondrial matrix. The energy generated by the H^+ "waterfall" spins the ATP Synthase, generating ATP.

The process of oxidative phosphorylation is illustrated in Figure 4.13. The process involves four separate *protein complexes*, identified as I–IV, each comprised of proteins, coenzymes, and cofactors. These types of molecules are able to carry electrons and pass them on to the next molecule in the chain. NADH and $FADH_2$ donate their electrons to the first two complexes in the chain; these electrons are then transferred to the next protein, and the next, in stepwise fashion. With each pass of an electron, a little bit of energy is released.

To understand this concept better, consider an analogy. Imagine you have a raw egg you wish to transport safely from the top of a tall balcony to the ground, without leaving the balcony yourself. You have plenty of helpers, but no other materials or equipment. You only have two choices: (1) drop the egg (which would certainly result in a yolky mess on the ground), or (2) have your friends line up on the stairs, and then carefully pass the egg from one person to the next until it can be gently set down. Each time the egg is passed to a person standing lower on the stairs, a small amount of gravitational potential energy is released into some other form of energy. The latter scenario is analogous to what happens in the electron transport chain (ETC). If NADH and $FADH_2$ were to release their electrons to O_2 all at once, the result would be an uncontrolled explosion of energy that would be disastrous for the cell, just as dropping an egg from a high balcony would be disastrous for the egg. The gentle release of energy as the electrons are sequentially passed to complexes down an energy "hill" allows for a controlled process.

Looking at the ETC in more detail, we begin at complex I, where NADH is oxidized to NAD^+ by the loss of two electrons, which are then passed to the next molecule. In the process, the negative charge of the electrons pulls up hydrogen ions (protons) into the membrane protein. As the electrons join with the next electron transport molecule, the H^+ are released on the other side of the membrane. In this fashion, the passing of electrons down the ETC results in protons being actively transported from the inner mitochondrial matrix to the intermembrane space.

At complex II, another mechanism is exploited. Here, $FADH_2$ becomes oxidized, releasing its electrons to a coenzyme Q (labeled in Figure 4.13 as Q). An H^+ joins as well to neutralize the charge. Now, coenzyme Q floats freely through the membrane. It travels to complex III, where the H^+ ion is released to the intermembrane space and the electron is passed on to the next molecule, cytochrome C (cyt c in the figure). Finally, in complex IV, four molecules of cyt c pass on their electrons to molecular oxygen (O_2), the final electron acceptor in the ETC. In this process, H_2O is formed, and four H^+ ions are pumped across the membrane. Interestingly, the activity of the complex IV enzyme (cytochrome C oxidase) is inhibited by both cyanide (CN^-) and carbon monoxide (CO).

What do think the result is of poisoning by either of these compounds? Suffocation from the inside! The reason we breathe oxygen is that O_2 serves as the final electron acceptor in the ETC. Without this process, our cells would not have nearly enough ATP to function. In the presence of small molecular inhibitors CN^- or CO, the entire ETC is halted, resulting in death.

Let's continue discussing Figure 4.13. Now that the ETC is complete, all the electrons produced from glycolysis and the citric acid cycle have been spent, resulting in a concentration gradient of H^+ across the membrane. In other words, the intermembrane space has a high H^+ concentration, while the matrix has a relatively

Figure 4.14. A hydroelectric power plant harnesses energy from the height difference in water, just as the ATP synthase harnesses energy from the concentration difference in H^+ across the membrane.

low one. To make a physical analogy, the pumping of H^+ out of the matrix is like a water pump that transports water up a hill. The net result is water with a lot of gravitational potential energy that can be harnessed if it falls back to the ground. In fact, this is exactly how hydroelectric power plants work to generate electricity, shown in Figure 4.14. As water falls down through turbines in a dam, the turbines spin an electric generator, generating electricity. Thus, the falling water converts gravitational potential energy into electrical energy.

In the mitochondria, instead of having water with high gravitational potential energy falling to an area of lower energy, there is high potential energy stored in a chemical gradient, and the H^+ ions "fall" from an area of high concentration to one of low concentration. The chemical term for this phenomenon is *chemiosmosis*. Recall that the force of water across a membrane is what drives osmosis. In chemiosmosis, a molecule other than water provides this force. Instead of falling through the turbines of a hydroelectric power plant, H^+ ions pass through the ATP synthase. This molecule is the rightmost transmembrane protein shown in Figure 4.13, and is also shown in the model of Figure 4.15. As protons pass through the ATP synthase via facilitated passive transport (facilitated diffusion), they interact with portions of the protein that resemble a turbine. In fact, the force of the H^+ ions literally makes the ATP synthase spin! As it spins, the ATP synthase catalyzes the addition of inorganic phosphate to ADP, forming ATP molecules.

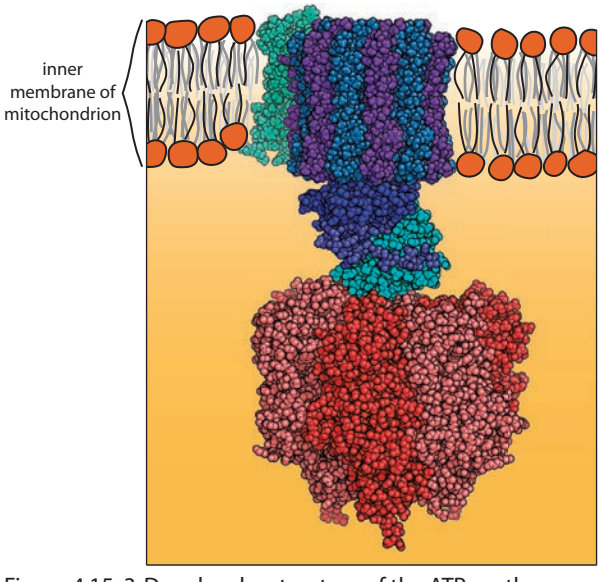


Figure 4.15. 3-D molecular structure of the ATP synthase (individual atoms shown). The top portion (green/purple) sits embedded in the inner mitochondrial membrane. The bottom red portion spins as ATP is generated. H^+ ions flow through the enzyme, from top to bottom.

This elegant system produces quite a number of ATP molecules. It is difficult to say exactly how many, due to the numerous chemical reactions involved. The best estimates are 26–28 ATP molecules per glucose molecule. In combination with ATP formed during glycolysis (two ATP) and the citric acid cycle (two ATP), this makes for a total production of up to 32 ATP molecules.

It is amazing that the man-made mechanism for generating electricity—exploiting the principles of natural law—should so closely resemble the God-designed mechanism that powers living cells. The laws of nature, including the law of conservation of energy, govern both man-made and natural processes. Natural processes provide all that we need for life.

Oxidative phosphorylation may be summarized as follows:

1. Occurs across the inner mitochondrial membrane.
2. Driven by electrons carried by NADH and $FADH_2$ from previous stages.
3. Electrons are passed along ETC, losing energy as they go.
4. Energy from electrons drives active transport of H^+ into intermembrane space.
5. O_2 is the final electron acceptor in the ETC.

6. H^+ ions fall back into the matrix through ATP Synthase (chemiosmosis), driving ATP synthesis.
7. Approximately 26–28 ATPs are formed in this final stage of cellular respiration.

4.2.3 Aerobic Respiration, Fermentation, and Anaerobic Respiration

The cellular respiration process described at length in Section 4.2.2 is only one of three processes cells use to generate energy. In this subsection, we distinguish between these three processes and briefly describe the other two.

As we have seen, when oxygen is available, it is the final electron acceptor in cellular respiration. In this case, cellular respiration is an *aerobic* process. Aerobic means "requiring air," although it is actually the oxygen in the air that is required. Thus, respiration in the presence of oxygen is *aerobic respiration*. Indeed, the role of O_2 as final electron acceptor in the ETC means that the Krebs cycle and oxidative phosphorylation cannot proceed in the absence of oxygen.

The other two energy processes occur in the absence of oxygen. The first is called *fermentation*, illustrated in Figure 4.16. The absence of oxygen is called an *anaerobic* ("without air") condition. Some tissues, such as muscle, use fermentation as a backup plan for generating ATP under anaerobic conditions. Normally, when enough O_2 is available, the pyruvate formed in glycolysis is oxidized by CoA and then proceeds through the citric acid cycle. However, during periods of intense exercise, there may not be enough O_2 to keep up with the demands of the cell. In this instance, pyruvate goes into an alternate pathway, allowing glycolysis to continue. If the alternate pathway did not exist, then NADH could not be recycled into NAD^+ that the glycolysis pathway needs to continue breaking glucose into smaller organic molecules. In the alternative scenario, the way NAD^+ is regenerated is by coupling the $NAD^+ \rightarrow$ NADH reaction to the conversion of pyruvate into a molecule called *lactate*. In this way, muscle cells can keep generating ATP through glycolysis. You may have heard that during intense exercise lactic acid builds up in muscle tissue. This lactic acid is from the lactate generated by fermentation.

As an aside, aerobic exercise is so called because it increases the ability of the cardiovascular and respiratory systems to deliver O_2 to the cells. This enables the muscles to work harder and

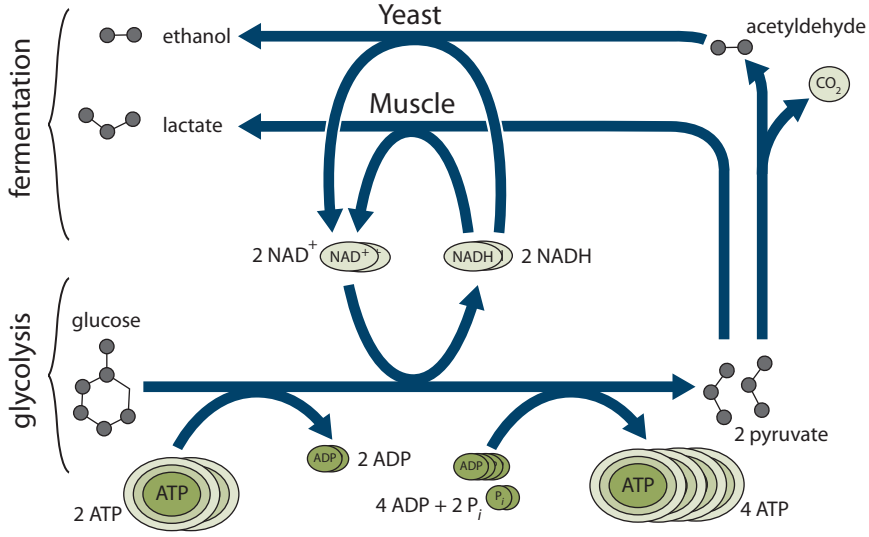


Figure 4.16. Fermentation. In the absence of O_2, glycolysis continues so long as there is a way to recycle NAD^+. Yeast accomplish this by converting pyruvate into ethanol. Muscle cells instead convert pyruvate to lactate.

Figure 4.17. The Fountain Paint Pots at Yellowstone National Park contain anaerobic bacteria that reduce sulfate rather than oxygen. The resulting H_2S molecule gives this geologic wonder its characteristic smell of rotten eggs.

longer without the build-up of lactic acid.

In addition to its occurrence in muscle tissue, fermentation appears in many other natural processes. A number of species of bacteria and yeast undergo fermentation. In these instances, pyruvate is transformed into either lactate or ethanol, the primary constituent of alcoholic beverages. Beer and wine making involve transformation of glucose into alcohol by fermentation. Barrels are used to provide the oxygen-free environment for this process. Additionally, the yeast used in bread-making undergo a process of fermentation, forming CO_2 bubbles and ethanol. These products cause bread to rise and give bread its characteristically pleasant aroma, as the ethanol is evaporated during baking.

Fermentation is one way species generate ATP in the absence of oxygen. There is another possibility, used by microorgansims living in environments where there is no oxygen. Such microorganisms use a different molecule as the final electron acceptor in their electron transport chains in the process called *anaerobic respiration*. One such molecule is sulfate (SO_4^{2-}), which is reduced into hydrogen sulfide (H_2S). Hydrogen sulfide is easily recognized by its characteristic odor, generally described as a rotten-egg smell. If you've ever been to Yellowstone National Park, shown in Figure 4.17, you may have smelled this stinky result of anaerobic respiration.

Finally, we should also note that while prokaryotes (which are all microorganisms) do not have mitochondria, they do run the electron transport chain across their plasma membranes.

To recap, there are three types of cellular respiration. Aerobic respiration uses O_2 to accept electrons through the ETC. Fermentation proceeds in the absence of oxygen through glycolysis only, allowing NAD^+ regeneration. Ethanol (alcohol) and lactate are possible byproducts. Finally, anaerobic respiration occurs in microorganisms that use other molecules besides O_2 to accept electrons from their ETC.

4.3 Photosynthesis

Cellular respiration harnesses energy from organic molecules (food) and O_2, generating ATP for cells to use. Carbon dioxide is a waste product. In a sense, *photosynthesis* is the reverse process. Photosynthesis harnesses sunlight to synthesize sugars out of CO_2 and H_2O, with oxygen as a waste product, as illustrated in Figure 4.18.

Though only certain types of organisms (plants, algae, and cyanobacteria) undergo photosynthesis, the energy they store in sugars powers all life on earth! Non-photosynthetic organisms must consume other organisms to obtain food, whose energy originally came from the sun. Furthermore, the waste product of photosynthesis (O_2) is necessary for other organisms to breathe. Cellular respiration and photosynthesis are two interdependent processes, without which no life could exist at all. Once again, this carefully designed, interdependent system dis-

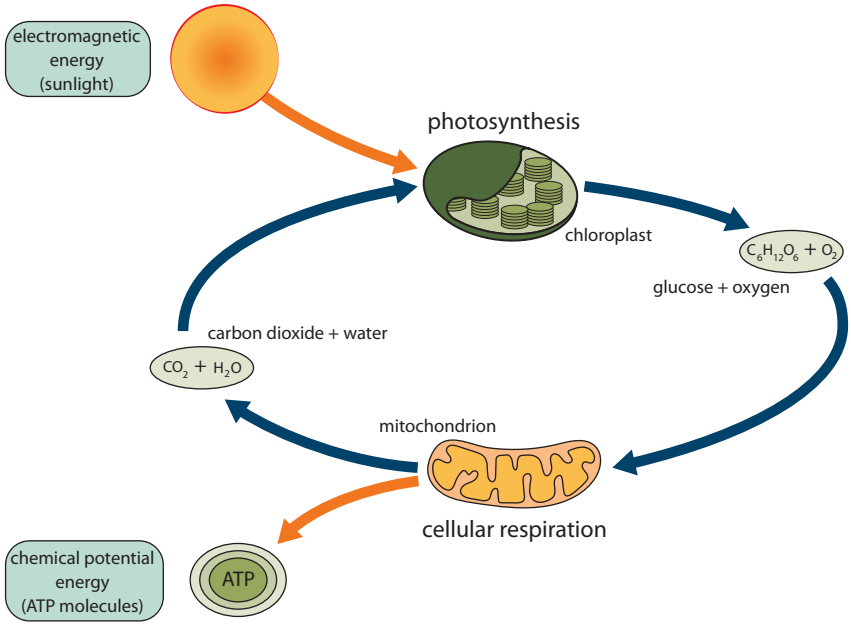


Figure 4.18. The interdependence of cellular respiration and photosynthesis. The waste products of one process serve to power the other. In this way, all life on earth is powered by energy from the sun. Note that although glucose is shown here as the primary sugar produced, simpler sugars are the ones directly made by photosynthesis. These are then precursors to synthesis of many biomolecules in the cell, including glucose.

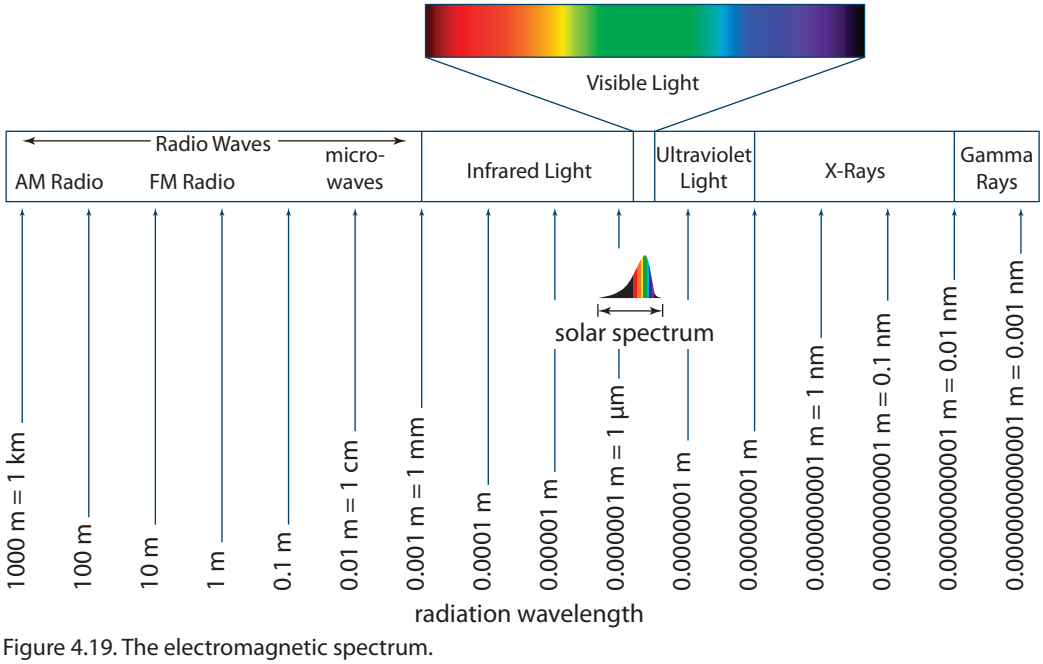


Figure 4.19. The electromagnetic spectrum.

plays God's intricate care for his creatures, evident in the chemical reactions of molecules, the machinery of cells, and in interdependence of different species throughout ecosystems.

4.3.1 Light and the Electromagnetic Spectrum

Understanding photosynthesis requires familiarity with electromagnetic radiation or waves, so we begin here. Electromagnetic waves are a form of pure, massless energy that are able to travel through empty space. Electromagnetic waves include radio, visible light, and X-rays all as part of the *electromagnetic spectrum*, illustrated in Figure 4.19. The only characteristic that distinguishes one part of the electromagnetic spectrum from another is the wavelength of the waves.

In a vacuum, all wavelengths of electromagnetic radiation travel at the same speed—300 million meters per second. However, depending on the wavelength, they carry various amounts of energy. Lower energy waves have longer wavelengths; higher energy waves have shorter wavelengths.

As shown in Figure 4.19, the longest wavelength waves are radio waves. These waves transmit signals from radio stations to receiving antennas on AM and FM radios. The wavelengths

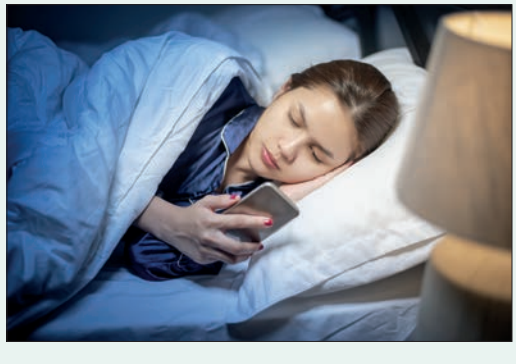
Hmm... Interesting. — *Light and Humans*

Though humans cannot undergo photosynthesis, special sensitive cells in our eyes and skin do render many of our physiological processes sensitive to light. We humans may not be able to make our own food via photosynthesis, but we are sensitive to light!

In addition to the cells in our eyes responsible for vision, we have photosensitive cells that detect current levels of light exposure (even through closed eyelids) and send signals to the universal timekeeper of our bodies—a region of our brain called the SCN. In low-light or dark conditions, the SCN signals for *melatonin* production. Melatonin is a hormone that causes us to feel sleepy. During daylight hours, melatonin production stops.

Under normal conditions, light exposure leads to a 24-hour sleep/wake cycle (circadian rhythm) that is tied into many other aspects of our physiology, including metabolism, mood, learning, and memory. When the time periods of light and dark exposure are disrupted—such as when flying to another part of the world—the body takes a few days to adjust to the new location, causing the body to experience the fatigue and irregular sleep patterns of jet-lag. Shift workers often have trouble keeping a consistent circadian rhythm when they must sleep during the day and work at night. In far northern regions where winter days are very short, the depressive symptoms of SAD (seasonal affective disorder) are a common problem.

Research indicates that short-wavelength light is especially activating to the SCN. Commonly called "blue light," it is a major component of the light emitted from screens such as those on smart phones. Perhaps, then, excessive use of one's smart phone right before bed isn't the best way to keep one's circadian rhythm in sync. Lots of light exposure during the day (go outside!) and limited exposure at night is the pattern that best maintains your circadian rhythm.



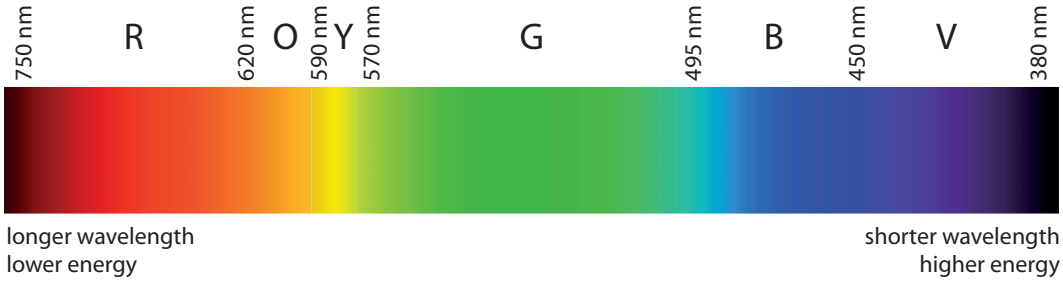


Figure 4.20. The visible light portion of the electromagnetic spectrum showing approximate reference wavelengths for different colors.

of these waves is on the order of meters to kilometers. At the opposite end of the spectrum are gamma rays. These waves pack so much energy that they only come from highly energetic sources, such as nuclear decay of radioactive elements and from high-energy astronomical objects, such as pulsars and quasars. This kind of radiation is strong enough to damage human tissue (one of several reasons why the use of nuclear weapons is so devastating). On the flip side, doctors have harnessed this type of radiation to treat some cancer patients. In a procedure called the "gamma knife," doctors concentrate gamma rays to deliver a maximum of damage to cancer cells with a minimum of damage to surrounding healthy tissues. Gamma rays have a very tiny wavelength—smaller than the size of an atom. Because the wavelength of gamma rays rivals the size of electrons, protons, and neutrons, gamma rays can travel through matter (remember that atoms are mostly empty space!) and cause substantial damage whenever they collide with subatomic particles.

The other regions of the electromagnetic spectrum are shown in Figure 4.19, and have intermediate wavelengths between those of radio waves and gamma rays. In the center of the spectrum lies visible light, the only part of the electromagnetic spectrum that humans can detect with their eyes. The visible spectrum can be further divided by specific wavelength, each wavelength range corresponding to a different color, as shown in Figure 4.20. These wavelengths range from 700 nm to 400 nm, about the size of small bacteria. The fact that the wavelength range of visible light is on the order of a bacterial length is what makes the light microscope a great tool for observing cells (but not organelles!). Specific wavelengths of light are important for the role of sunlight in photosynthesis, as we see in the next section.

4.3.2 Chlorophyll Molecules

In the first step of photosynthesis, electromagnetic radiation (light) is captured and converted into chemical potential energy, a process that occurs in the chloroplasts of cells. As you are probably aware, light exhibits both wave-like properties and particle-like properties. When discussing the particle-like properties, we refer to the individual, massless particles of light as *photons*. The real biological solar panels present in the chloroplasts are special photoreactive molecules, whose chemistry allows for photons of light to excite individual electrons into high-energy states. In other words, the electrons absorb the energy of the photons and move to higher-energy orbitals in the atom. The energized electrons are then free to fall to lower-energy states through an electron transport chain in a fashion very similar to the one used in cellular respiration.

Figure 4.21 illustrates the most important of these photoreactive molecules—*chlorophyll a*. The chemical bonds of this molecule allow its electrons to have only very specific energies. Recall that electrons in atoms are only allowed certain energies and the orbitals they are in depend on the energy they have. One consequence of these specific energies is that each electron in an atom can only absorb electromagnetic radiation (photons) of a very specific wavelength. If the

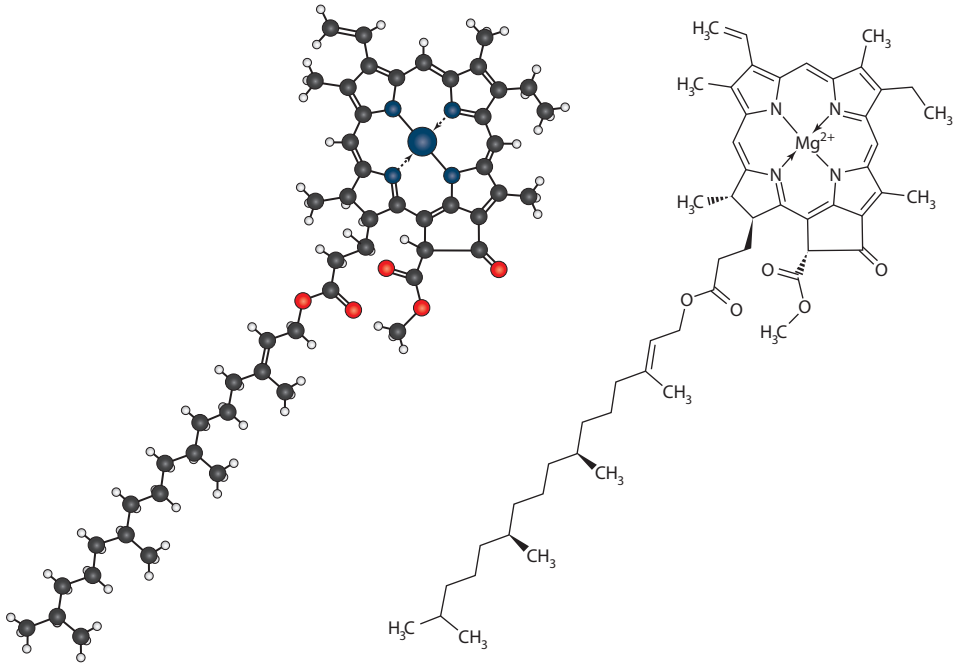


Figure 4.21. Chlorophyll a.

wavelength of light matches the energy required for an electron to jump to an excited state, the electron absorbs the energy of the light and is excited to a higher-energy orbital or freed into another chemical process altogether. If the wavelength of light doesn't match the energy required for the electron to change energy states, the light is reflected or simply passes through (transmitted). The reflected wavelengths of light give objects the colors we see—after reflecting, rays of light travel to our eyes where they are detected and interpreted by our brains as particular colors.

The phenomena of absorption and reflection explain why plants appear to be green. The *absorption spectrum* of a molecule is represented by a graph showing the strength of the molecule's light absorbance versus wavelength. Figure 4.22 shows the absorption spectra of the molecules chlorophyll a and chlorophyll b. Where the curve is high in this graph, light is strongly absorbed by the molecule; where the curve is low, light is mostly or all reflected. Notice that both molecules absorb strongly in the blue and red regions, but they absorb almost nothing in the green region of the spectrum. Consequently, red and blue wavelengths are absorbed and green wavelengths are reflected, causing us to see green when we look at the leaves of plants. Figure 4.23 shows the chloroplasts in plant cells. The chloroplasts are green because of the chlorophyll molecules they contain.

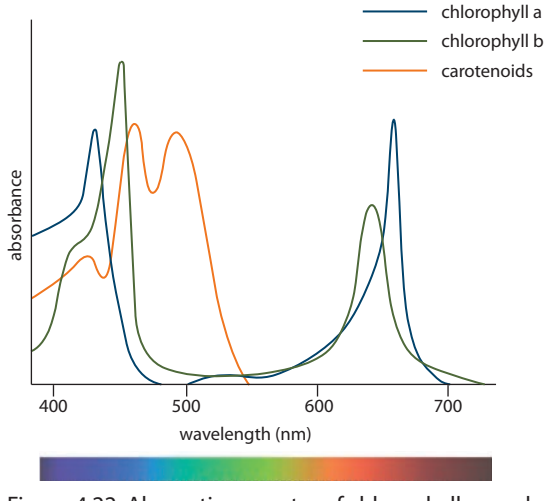


Figure 4.22. Absorption spectra of chlorophylls a and b and the carotenoid pigments.

While we are on the subject of the colors of leaves, Figure 4.22 also shows the absorption spectrum of the carotenoids, one of the many pigments in plant leaves. Carotenoids are responsible for the yellow colors in many differ-

ent plants and animals. In plants, the yellows of the carotenoids are masked by the presence of green chlorophyll. In the autumn, they provide one of the dominant colors in the leaves of deciduous trees.

Before reading about the process of photosynthesis, you may wish to review the structure of chloroplasts in Section 3.2.3.

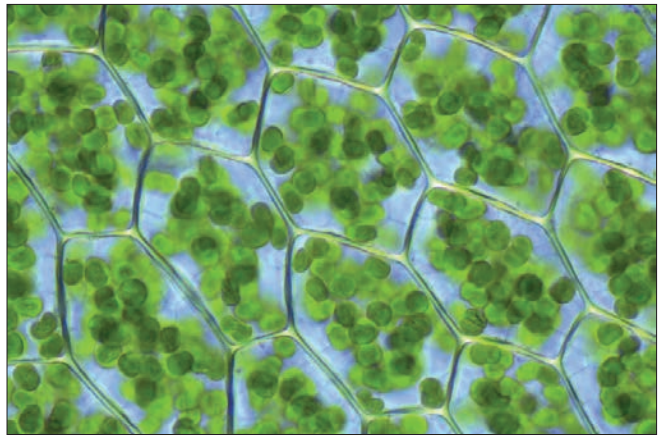


Figure 4.23. Chlorophyll molecules are concentrated in the chloroplasts of plant cells. In this light microscope image, you can see that only the chloroplast organelles (small green circles) appear green, not the other organelles (which appear to be transparent). Notice the clearly visible cell walls.

4.3.3 The Light-Dependent Reactions

By absorbing the energy in sunlight, the chlorophyll molecules power the process of photosynthesis. Figure 4.24 shows a schematic overview of this process. The overall purpose of photosynthesis is to convert CO_2 into sugars, using energy from the sun. The byproduct of this series of chemical reactions is oxygen. The chlorophyll molecules are embedded in the thylakoid membrane of the chloroplast as part of a large protein complex. Here, the first phase of photosynthesis—the *light-dependent reactions*—occurs. The purpose of the light-dependent reactions is to synthesize ATP and NADPH, using energy from light and releasing O_2 as a waste product. NADPH is an electron carrier molecule similar to NADH, differing only by the presence of an extra phosphate group.

The light-dependent reaction can be expressed as follows:

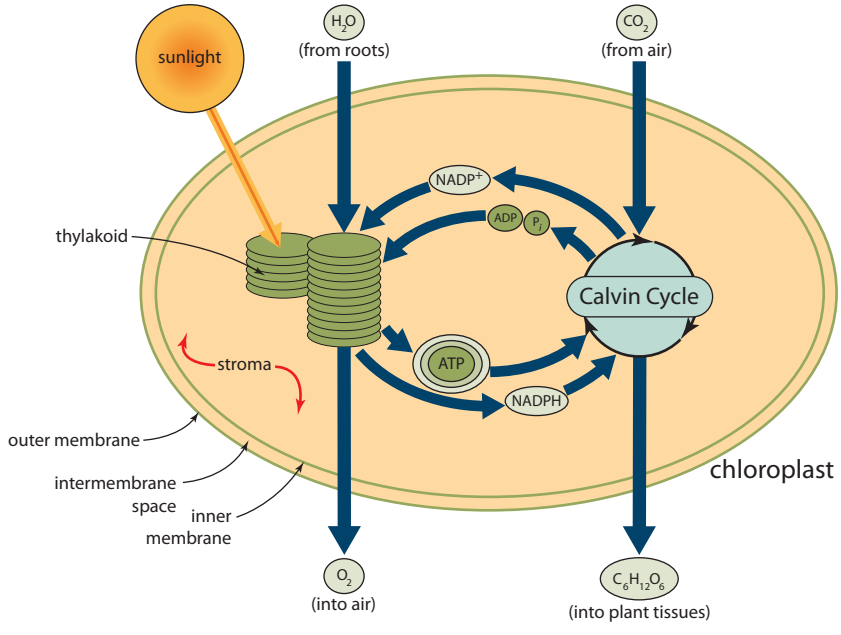


Figure 4.24. A schematic overview of photosynthesis.

$$ADP + NADP^+ + P_i + H_2O \xrightarrow{light} O_2 + ATP + NADPH$$

As illustrated in Figure 4.25, the light-dependent phase of photosynthesis uses an electron transport chain mechanism to drive chemiosmosis of H^+ through an ATP synthase, in a manner similar to the process that occurs in cellular respiration. The first protein complex embedded in the thylakoid membrane, shown on the left side of the figure, is Photosystem II (PS II). (Don't be confused by the name. PS II is so called because it was discovered after Photosystem I, even though it is the first step in the pathway). PS II has chlorophyll and other photoreactive molecules embedded in it. As the electrons of these photoreactive molecules are excited and passed down the electron transport chain (the path indicated by the red arrows), electrons are ripped from water molecules in order to replace those of the chlorophylls, which are exiting to the electron transport chain. As the water molecules are ripped apart, they produce molecular oxygen (O_2, the waste product) and H^+ ions.

As electrons proceed down the electron transport chain, complexes PQ and b6f pull H^+ ions from the stroma and actively transport them into the thylakoid lumen. The electrons enter Photosystem I (PS I), another complicated multi-protein complex. There they require an extra boost of energy in order to proceed. This boost is provided by light harnessed by chlorophyll and other photoreactive molecules. The final step of the ETC results in the reduction of $NADP^+$ to NADPH.

Finally, a large concentration gradient of H^+ builds up in the thylakoid lumen, due to active transport of H^+ and as a byproduct of splitting water. These H^+ ions travel through the ATP synthase out into the stroma, catalyzing the formation of ATP, just as in cellular respiration.

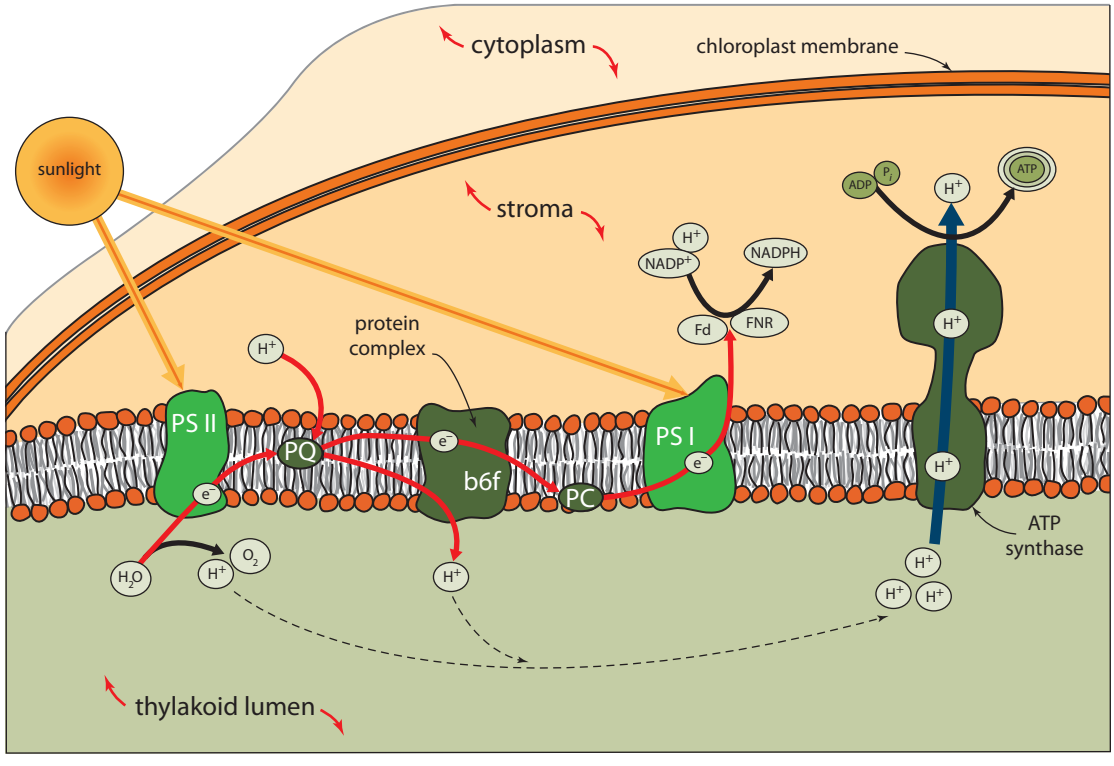


Figure 4.25. The light-dependent phase of photosynthesis.

With the formation of ATP and NADPH, we now have the high-energy molecules needed to carry out the second phase of photosynthesis, the Calvin cycle.

4.3.4 The Calvin Cycle

The second phase of photosynthesis, called the *light-independent* phase or *Calvin cycle*, uses the energy stored in ATP and NADPH to run the reaction

$$CO_2 + H_2O \rightarrow \text{sugars}$$

The Calvin cycle is named for American biochemist Melvin Calvin (Figure 4.26), who studied the pathway along with colleagues Andrew Benson and James Bassham. Their technique involved labeling or marking compounds with atoms of carbon-14. The radioisotope-labeling technique allowed Calvin to trace a particular carbon atom through the entire pathway. For this work, Calvin was awarded the 1961 Nobel Prize in Chemistry.

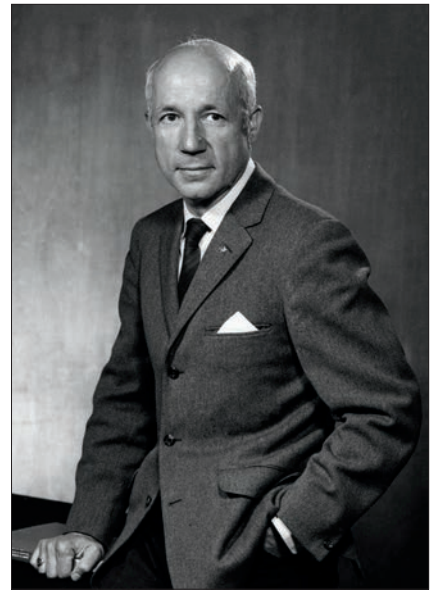


Figure 4.26. Melvin Calvin (1911–1997).

The purpose of the Calvin cycle is to synthesize sugars out of CO_2, using energy supplied by ATP and NADPH

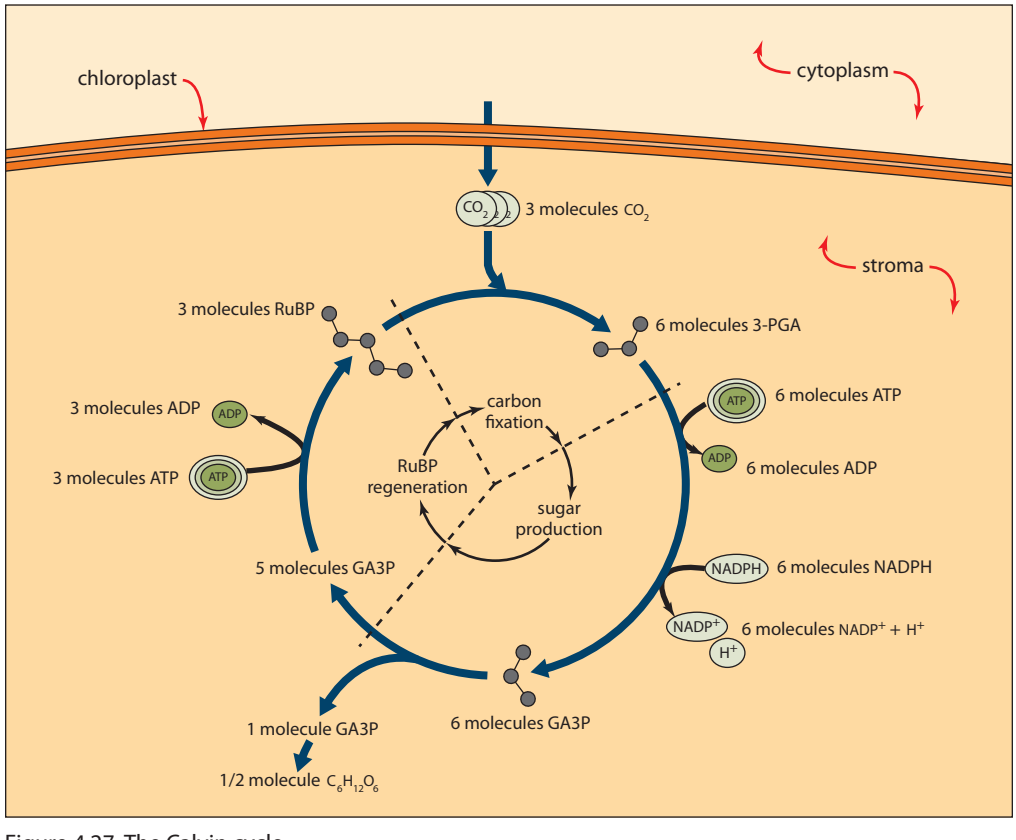


Figure 4.27. The Calvin cycle.

from the light-dependent phase of photosynthesis. The Calvin cycle takes place in the stroma of the chloroplast.

Figure 4.27 shows each phase of the Calvin cycle in more detail. In phase 1 (carbon fixation), three CO_2 molecules from the atmosphere join with three five-carbon molecules (RuBP) already in the cycle. This step is catalyzed by an enzyme nicknamed RuBisCO. One CO_2 combines with one RuBP to form a short-lived six-carbon molecule, which splits into two three-carbon entities, called 3-phosphoglycerate (3-PGA), for a total of six molecules. Next, using ATP and NADPH from the light-dependent reactions, 3-PGA is reduced into glyceraldehyde 3-phosphate (GA3P). GA3P is the primary product of the Calvin cycle. It is the precursor to a number of larger molecules, including glucose, that the cell synthesizes. Of the six GA3P molecules synthesized, only one goes on towards other metabolic pathways. The remaining five are regenerated (through a number of steps not shown here) back into RuBP to begin the cycle again. This regeneration step uses three ATP molecules from the light-dependent pathway.

The Calvin cycle may be summarized as follows:

1. Three CO_2 molecules enter from the environment (cytoplasm and stroma)
2. These are converted into the sugar precursor GA3P.
3. Energy for this process comes from ATP and NADPH generated by the light-dependent photosynthetic reactions.

4.3.5 Adaptations for Arid Climates

Most plants undergo the regular photosynthesis described above, which also goes by the name of C3 photosynthesis. For example, rice, shown in Figure 4.28, a major food source for human beings, is a C3 plant. However, there are some plants in hot, dry climates that must make some modifications in order for photosynthesis

Figure 4.28. Rice, a staple crop for many populations, is a C3 plant.

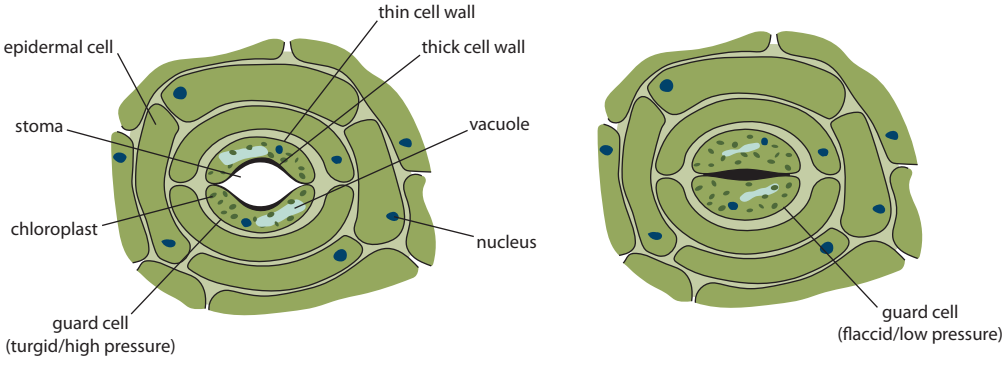


Figure 4.29. Stomata, openings in leaves that allow for entrance of CO_2 and exit of H_2O. The stomata open when water is abundant and close when water is scarce.

Figure 4.30. Corn is a C4 plant, separating steps of the Calvin cycle into different cell types so as to concentrate CO_2 while retaining water.

Figure 4.31. Sugarcane, another C4 plant.

to function properly. There are two major alternative strategies that we mention here: C4 photosynthesis and CAM photosynthesis.

As illustrated in Figure 4.29, leaves in plants have passages, called *stomata*, that open to allow environmental CO_2 to enter and H_2O molecules to escape, a process known as *transpiration*. The cells surrounding the stomata—called guard cells—enable them to open when cells have excess water (so that the water may evaporate) and close when cell vacuoles do not have enough water (to prevent too much water loss).

In hot, dry climates, plants close their stomata to prevent too much water loss. The side effect of stomata closure is that not enough CO_2 is present for photosynthesis, causing the Calvin cycle to use O_2 instead of CO_2. This wastes energy but helps keep the plant alive.

C4 plants, such as the corn and sugarcane shown in Figures 4.30 and 4.31, avoid this wasteful scenario by separating parts of the Calvin cycle into different cell types. In this way, CO_2 is collected and stored in one particular cell type at high concentration, enabling the Calvin cycle to run normally.

Another strategy is utilized by CAM plants, such as pineapple, shown in Figure 4.32. CAM plants separate the metabolic processes by night and day. To prevent excessive water loss, the plants open their stomata at night, allowing entrance of CO_2, which is stored by reaction with organic carrier molecules. During the daytime, the stomata close, but the stored CO_2 is still available to run the rest of the Calvin cycle.

Figure 4.32. Pineapple uses another photosynthetic strategy, the CAM pathway, in which metabolic processes are separated by night and day.

Chapter 4 Exercises

SECTION 4.1

1. Given the following chemical reaction, identify the reactants and the products.

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

2. Explain the role of a catalyst in a chemical reaction.

3. Compare and contrast combustion, redox, and hydrolysis reactions.
4. Classify the following chemical reactions as combustion, redox, or hydrolysis:
   a. sucrose + water → glucose + fructose
   b. $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$
   c. $4Fe + 6O_2 \rightarrow 3Fe_2O_3$
   d. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
   e. triglyceride + base + water → soap
5. Explain why ATP is the ideal energy currency for the cell.
6. Distinguish between endothermic and exothermic chemical reactions.
7. Draw and label two reaction coordinate diagrams: one for an exothermic reaction and one for an endothermic one. Make sure to include the pathways with and without an enzyme.
8. Describe in detail how enzymes facilitate biological chemical reactions.
9. Explain the process of feedback inhibition in a series of enzyme-catalyzed chemical reactions.

SECTION 4.2

10. What is the overall purpose of cellular respiration?
11. Make a table that lists the inputs, lists the outputs, and describes the overall results for each of the four stages of cellular respiration.
12. Using your table from the previous exercise, describe in words how each of the four stages of cellular respiration contribute to the overall purpose. (Describe the process and intermediate results accomplished by each phase.)
13. During glycolysis, how many ATPs are invested and how many are generated?
14. Describe the role of coenzyme A in cellular respiration. How does this prepare pyruvate for entrance into the citric acid cycle?
15. Describe the function of NADH and $FADH_2$ in glycolysis and the citric acid cycle.
16. Name two major scientists who contributed to our understanding of the citric acid cycle and describe their findings.
17. What happens to the CO_2 generated in the citric acid cycle?
18. Where in the cell do glycolysis and the citric acid cycle take place?
19. Write paragraphs that summarize the overall chemical transformations that occur in glycolysis and the citric acid cycle.
20. How is active transport used in the electron transport chain?
21. Describe what happens to the potential energy of each electron as it is passed down the electron transport chain.
22. Describe the mechanism by which coenzyme Q transmits electrons.
23. What is the final electron acceptor of the ETC? What happens to energy production in its absence?
24. Describe how poisons such as cyanide and carbon monoxide affect cytochrome c oxidase (the final enzyme in the electron transport chain of cellular respiration).

25. Compare the chemical gradient of H^+ ions across the inner mitochondrial membrane to the process by which hydroelectric power is generated.
26. Describe the mechanism of the ATP synthase.
27. Summarize the steps that occur in oxidative phosphorylation. How do these steps contribute to the overall goal of oxidative phosphorylation?
28. Compare and contrast aerobic respiration, anaerobic respiration, and fermentation.

SECTION 4.3

29. What is the overall goal of photosynthesis?
30. Explain why photosynthesis and cellular respiration are interdependent.
31. Name the colors of light that are most absorbed by plant pigments such as chlorophyll.
32. Suppose a person decides to grow some plants in a basement under green-light emitting lamps. Describe the results one should expect from this project.
33. Some foods, such as carrots and squash, appear to be orange/yellow. Based on what you know about absorption and pigment molecules, form a hypothesis as to why these vegetables display these colors.
34. How does the arrangement of electrons in atoms relate in general to the spectrum of colored light that a particular compound absorbs? How does this arrangement determine the color that a compound appears?
35. Briefly describe how the light-dependent and light-independent phases of photosynthesis contribute to its overall goal.
36. Compare and contrast the electron transport chain of photosynthesis to that of cellular respiration.
37. Name and describe two mechanisms by which the H^+ concentration gradient is created during the light-dependent phase of photosynthesis.
38. Briefly describe the mechanism of the Calvin cycle.
39. Compare and contrast the Krebs cycle and the Calvin cycle.
40. Explain two strategies used by plants in dry climates to minimize water loss during photosynthesis.

REVIEW QUESTIONS

41. Briefly describe the six requirements for life.
42. How does the capacity to cycle matter and energy (a characteristic of life discussed in this chapter in detail) interrelate with the other characteristics of life?
43. Of the classes of biomolecules discussed in Chapter 2 (carbohydrates, lipids, proteins, and nucleic acids), which types do you see at play in cellular respiration and photosynthesis? Identify as many as you can.
44. List as many cell organelles as you can. Identify the ones involved in photosynthesis and those involved in cellular respiration. For those involved in one or the other of these processes, describe their roles.
45. Define active transport and discuss several ways this can be accomplished across a cell membrane. Which of these modes are involved in photosynthesis and cellular respiration?
46. Define passive transport and discuss several ways this can be accomplished across a cell membrane. Which of these modes are involved in photosynthesis and cellular respiration?