FUNDAMENTALS OF HUMAN BIOLOGY & HEALTH

By Heather Murdock

FOURTH EDITION

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DEDICATION

This is dedicated to my daughters, Ella and Gillie. I love their curiosity, fascination, and sense of humor when it comes to the human body!

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Many thanks to my wonderful family and friends for their encouragement and support during this project, especially Gillian, Ella, and Paul. I'm also very appreciative of my San Francisco State University students, past and present, for all of their excellent questions and comments during class. I have incorporated many of these into this text. It's much more fun to teach when students are engaged and interested in what they are learning. I have always been very impressed with the students at SFSU in this regard. I have a handful of students who really helped me by providing their typed class notes so that I would know what I actually ended up writing on the board. Contributions from Joe Bernisky, Diana Rosas, Cheyenne Snavely, and Kristina Stuckenbrock are all very much appreciated. Thank you to Dr. Alan Salamy and Allen Hatchett for reading this manual and providing feedback and suggestions. Thank you also to everyone who helped put this reader together from Cognella Academic Publishing, especially my excellent copy editor Sharon Hermann. And most of all, thank you to my mom and dad for always enthusiastically encouraging me throughout my education, I'm happy to pass along what I've learned to others.

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PREFACE

THIS TEXTBOOK IS BASED ON MY LECTURE NOTES FROM PAST semesters of teaching human biology lectures and general biology laboratories at San Francisco State University. I have taken the information from a variety of sources listed in the bibliography, including books, magazine and newspaper articles, health journals, and Internet sources. This is not a complete picture of the human body and how it works. It is more a summary of the basic forms and functions of different systems in our incredible bodies along with some topics that I think students might find interesting and relevant. I have written this book because I think there needs to be a more affordable option than the $150 dollar price tag usually associated with human biology textbooks. We are all dealing with budget issues these days, especially in relation to education. I realize many students reading this are not biology majors and may never have to study biology again, but I hope I can relay the basics so that you will have a solid understanding of how human cells, tissues, organs, and organ systems operate, as well as knowledge that will allow you to make good choices about what you do with your own bodies. I will be focusing on basic health issues, including nutrition, exercise, and disease prevention, as well as reinforcing why we need to help one another and the planet.

Because this is really just skimming the surface of every topic, I encourage you to read other books to supplement your knowledge, especially for the subjects that you find interesting or that you don't fully understand just from my simplified coverage. It's also great to seek other sources for more pictures and diagrams because visuals are very helpful when learning a new subject. (You can pretty much Google anything these days!) This textbook is a work in progress, and I will be adding to it for future semesters. The study of biology is constantly evolving, and I learn new information every time I teach a class. I find that my students have a lot to teach me, as well, so let's learn together and hopefully have some fun in the process.

—Heather

Introduction to Biology and the Diversity of Life

CHAPTER 1

BIOLOGY IS THE STUDY OF LIVING ORGANISMS AND THEIR CHARacteristics. I think everyone should have a basic understanding of this science. Biology relates to everything about us: who we are, where we came from, what we are composed of, how we function, how organisms are interrelated, how the choices we make affect our own bodies as well as those around us and our planet. I hope some of the topics covered in this book will inspire you to lead healthy lifestyles and to respect other organisms and ecosystems. Learning about basic biology may also inspire you to delve into one of the numerous biological fields. There are new discoveries all of the time, and it's a very exciting subject to study.

Biology has led to the prevention and treatment of so many diseases, with lifesaving advances such as vaccines, antibiotics, chemotherapy, dialysis, anaesthesia, and surgical procedures. We also understand how organisms have evolved over time and can compare DNA and morphological features of different organisms and fossils to see how species are related. Now we can even map the entire human genetic code, an international scientific project that took 13 years to complete! There are so many interesting careers associated with biological studies, such as zoologist, doctor, dentist, teacher, pharmacist, physical therapist, ophthalmologist, game warden, landscape architect, veterinarian, geneticist, paramedic, conservation biologist, environmental consultant, pathologist, dietitian, nurse, lab technician, dermatologist, medical illustrator, oceanographer … the list goes on and on.

If this hasn't grabbed your interest, then maybe some of the amazing statistics we'll be covering about the human body will fascinate you. We are so efficient at balancing our temperature, water, and electrolyte levels; using nutrients; making energy; eliminating waste; fighting disease; sorting and storing data in our brain; reproducing; and responding to our environment inside and out! We will be discussing the following topics throughout the book, but here are a few fun facts to throw out at parties to impress your friends.

JUST A FEW FACTS ABOUT THE HUMAN BODY

There are two million species classified on our planet today, but it has been extrapolated that there have been anywhere from five to 100 million living and fossil species from when life began (3.8 billion years ago!).

Modern humans have been around for 195,000 years.

Human, chimpanzee, and bonobo DNA sequences are about 98% the same!

Humans have 46 chromosomes, which consist of approximately 25,000 genes, coding for all of the traits that make us who we are.

An adult human is made up of 80–120 trillion cells, 25% of which are red blood cells.

There are over 200 different types of cells, all made from stem cells. Most are microscopic (you could line up 2,000 blood cells across your thumb), but we have larger cells, too, like the neurons in nerves that stretch over three feet long!

Speaking of nerves, if you lined up all of the peripheral nerves in your body (the nerves in areas other than the brain and spinal cord), they would be 93,000 miles long!

We can send 300 messages per second with our nerves, and the impulses can travel 395 feet per second (over 150 miles per hour). We generate enough electricity with the billion neurons in our brain to power a light bulb (or turn on a flashlight)!

We have ten million chemoreceptors in our nose to help us recognize 10,000 odors. Odor is the strongest trigger for memories.

We have 2.5 million sweat glands, on average; sweat is one of the main ways we lose water from our bodies, but it's also very important to help us cool down when we get too hot.

We have trillions of skin cells covering our bodies (3–10 trillion, depending on the size of the body), and we shed about a million skin cells a day! This makes up most of the dust around your house! (Yikes)

The average adult head has 120,000 hairs; however, averages tend to vary by pigmentation: 140,000 for blondes and more like 90,000 for redheads. We lose about 100 hairs per day.

Half of Our Bodies Are Made Up of Muscle

Half of human body tissue is composed of muscle. (We have three types—skeletal, smooth, and cardiac muscles.) There are 640 skeletal muscles, the largest of which is the gluteus maximus (which helps form the buttocks and gives it a rounded shape). All of the skeletal muscles working together in an adult body could lift 11 tons, which is equivalent to four SUVs!

The number of bones in your body depends on how old you are. As babies, we start out with 300 bones. They are soft bones at this stage, made of cartilage and easily pliable, which helps us to get out of the birth canal. They have all hardened completely into bone by the time we are 14 months old. As we develop, certain bones fuse together, and by the time we are 20 years old, most people have 206 bones. (However, some people have an extra rib and some have an extra bone in the arch of the foot, so the total can be 207 or 208 depending on your genetics.) Our body is composed of 18% bone.

The Heart Can Pump 5.6 Liters of Blood Continuously All Day

Our heart is a truly amazing organ made up of cardiac muscle. It can pump 5.6 liters of blood continuously all day (the equivalent of cycling 2,000 gallons a day). Each blood cell travels a complete circuit around the pulmonary and systemic circulatory systems within 60 seconds. The heart averages 100,000 beats per day. That can mean 2.5 billion beats in a 70-year life. If you added up all of our blood vessels (arteries, arterioles, capillaries, venuoles, and veins) they would reach about 64,000 miles. (That is over twice the circumference of the Earth!)

Our kidneys cycle 45–50 gallons of fluid every day by filtering our blood 30 times a day through the one million nephrons we have in each kidney. This process is incredibly important to help us remove our wastes (such as urea, uric acid, and creatinine) as well as excess water and salts and, in the process, reabsorb everything that we need to keep in our blood (like nutrients, electrolytes, and water).

The adult stomach can expand to hold two liters of food. Everything we eat is broken down into smaller particles throughout the digestive tract in an incredibly efficient manner. Most of what we need to keep is reabsorbed into our blood from the small intestines, which are almost 20 feet long. The small intestine has tiny projections called microvilli to increase the surface area of the tubules into 2,800 square feet (the size of a tennis court). Are you impressed yet?

Learning About Living Organisms

I am constantly amazed and fascinated by the human body. We often take our bodies for granted when everything is working perfectly. On the other hand, we can generally detect the slightest imbalance since it often causes many effects on how we function and feel. I hope reading this book will help to spark an appreciation for all of the trillions of parts we are composed of. They are working together in such an intricate manner to make us the incredible machines that we are.

This book focuses on humans, but we will discuss other types of organisms along the way since we are all interrelated. Living organisms are incredible on so many levels. What does it mean when we say "living organisms"? Seems pretty basic, but you need to know the definition of life in order to classify whether something is living or not. For example, viruses, although they can spread and cause great harm, are not actually classified as "living organisms." They do not possess all of the characteristics that the scientific community has come up with to define life.

Main Traits of Life

1. Living things are made up of **cells**. Organisms can be uni- (one celled) or multicellular (many celled).

2. Living things **respond to stimuli** in their environment through chemical receptors or some sort of nervous system—from the very basic to our incredibly complex nervous system.

3. Living things increase in size and/or number or cells (they **grow and develop**).

4. Living things **reproduce** new organisms of their own species and pass on hereditary material (in the form of DNA). Reproduction can be asexual (cloning themselves) or sexual (reproducing with a partner, which increases genetic variability). Reproduction is necessary for the survival of the species.

5. Living things use an **energy** source (from food) to fuel functions. Energy use is also known as **metabolism** where chemical reactions in the body break down nutrients and build compounds needed for life.

6. Living things maintain an internal environment that is favorable to cell function. The physical and chemical environment inside the body must be kept within certain limits that can support life. For example, we need to keep our body temperature around 98.6º F and the pH of our blood around 7.4; if blood is too acidic or too basic, our cells can't function—death can result from these conditions. "Staying the same" is also called "**homeostasis**." We have incredibly sophisticated feedback systems in order to maintain our homeostasis.

7. Living things may **adapt to environmental changes** resulting in an increased ability to reproduce. Darwin's Theory of Natural Selection states that the organisms that are best adapted to their environment will pass on the most genes. Species will change over time in the process we call evolution. Organisms have been evolving on Earth for the past 3.8 billion years. Before we can understand ourselves, we need to take a look at what has gone on before humans even inhabited the planet.

LIFE ON EARTH: HOW IT ALL BEGAN

Earth formed 4.6 billion years ago (bya)**.**

Life began roughly 3.8 bya (primitive anaerobic bacteria cells evolved, possibly from protobionts (organic molecules in a membrane-like structure).

Primordial atmospheric gases formed these organic molecules.We are still unclear of the process.

Photosynthesis by early bacteria three bya produced ***oxygen***, an important gas for other species to evolve.

Eukaryotic cells (more complex than prokaryotic cells) evolved 2 bya.

Complex **multicellular life** evolved one bya (colonies of cells like early **protista**).

Fungi are hard to pinpoint in the evolutionary record, but some studies believe early species appeared around 800 million years ago.

Simple animals, like sponges, evolved 665 million years ago (mya) from a type of protozoa called choanoflagellate.

Complex animals are in the fossil record around 550 mya (such as echinoderms, early chordates, arthropods, and mollusks, all of which were still in the sea; there were no terrestrial organisms yet).

Fish evolved from early chordates close to 500 mya.

Fungi started to colonize land around this same time.

Plants evolved from the protist algae charophyta around 475 mya.

Insects and **gymnosperm plants** (plants with "naked" seeds) came along 400 mya.

Dinosaurs and other **reptiles** evolved 300 mya after the **amphibians** (360 mya).

Mammals evolved 200 mya (small insectivorous egg-laying mammals came first, and the placental and marsupial mammals evolved 70 million years later).

Birds evolved from dinosaurs 150 mya.

Angiosperms (plants with enclosed seeds and flowers)came 130 mya.

Non-avian dinosaurs became extinct 65 mya; mammals radiated everywhere and evolved even more; the first primates showed up in the fossil records around this time.

Twenty-five mya, **ancestors of apes and humans diverged** from ancestors of old-world monkeys.

Distant bipedal ancestors of man occurred five mya.

2.5 mya, the **genus homo** is found in the fossil evidence.

200,000 years ago (ya), **humans started looking like they look today.**

25,000 ya, extinction of Neanderthals.

Population isolation, natural selection, and sexual selection caused different genetic traits in various populations, forming what we now call racial differences (skin color, hair color, hair texture, eye shape, and body stature).

(Dates prior to 1 billion years ago are speculative.)

DIVERSITY OF LIFE

There are so many different kinds of species on our planet. We've classified only about two million to date, but it's been extrapolated that there have been anywhere from five to 100 million living and fossil species on Earth! It's important to understand some basics about all of the major groups of organisms since we are all interconnected.

Scientists now group organisms into **three Domains**. Before 1990, they were usually grouped into **five Kingdoms**; since I'm old school, I still like the kingdom method, but I'll give you both here:

The three domains: **Archaea, Bacteria, and Eukarya.**
The five kingdoms: **Monera, Protista, Plantae, Fungi, and Animalia.**

Here are some of the defining characteristics of the domains and kingdoms.

The Three Domains

1. **Archaea**—unicellular prokaryotic organisms. (Prokaryotes don't have membrane-bound organelles, they just have free DNA, cytoplasm, and microtubules making flagella or cilia on the outside for movement.) Archaea usually live in extreme conditions without oxygen in places like swamps, volcano vents, landfills, salt water, and acidic water. They are VERY similar to the bacteria domain in form, but their gene sequences are different enough to classify them in a separate domain. (Although, when classifying organisms based on the kingdom method, I would still put the Archaea and Bacteria together.)

2. **Bacteria**—also unicellular and prokaryotic and are found EVERYWHERE! They are the types found in food, our bodies, soil, on plants, etc., etc. They are mostly **decomposers** and get food from outside sources—breaking down plant and animal matter and absorbing the nutrients into their cells—but some are **producers** and are able to make their own food through photosynthesis (using sunlight) or chemosynthesis (using chemicals). (This is also referred to as "autotrophic" = "self-feed.") Cyanobacteria (blue-green algae) are incredibly important since they started producing their own food three bya and, in the process, made oxygen, which led the way for most other species to evolve. Bacteria are the first kingdom in the old classification system.

3. **Eukarya**—the third and last domain is extremely diverse and holds the four other kingdoms—protista, plants, animals, and fungi—all of which have eukaryotic cells. Eukaryotic cells differ from prokaryotic cells in their complexity and the fact that they have discrete membrane-bound organelles performing different functions within the cells. We will cover the parts of the cell in Chapter 3, but some organelles that you have probably heard of are the mitochondria (to make energy), endoplasmic reticulum (to help make proteins), Golgi bodies (shipping and processing), and the nuclei (location of DNA synthesis and transcription). Some eukarya are autotrophic and can make their own food, such as the plants and various protista species. Many eukarya are called "heterotrophic" (other-feed) since they cannot make their own food and must get it from another source, either as a decomposer or a **consumer**.

The Five Kingdoms

Now let's break the classification down into the **Five Kingdoms**.

1. The most primitive kingdom is called **Monera**, which are all prokaryotic cells (see the Archaea and Bacteria description above). Over 10,000 species are known in this kingdom (but there could be millions that have not been discovered yet). For all of the rough estimates of species known per

kingdom, just realize that new species are being discovered all the time (about 15,000 per year) and that every source has different estimates, so it's hard to pinpoint the number of species for any of the kingdoms!

The **eukaryotic kingdoms** are:

2. **Protista***—many different kinds of protista exist (roughly 200,000 known species); some are producers, consumers, or decomposers; some are multi-, some unicellular; some don't have cell walls, and some do (cellulose or chitin). Some can move via flagella, cilia, or pseudopodia. They are sometimes classified according to whether they are animal-like (move and ingest other organisms), plant-like (can photosynthesize) or fungus-like (produce spores). Examples include paramecia, algae, slime molds, and parasites like plasmodium (causes malaria). An example of a protist that is very important for all life on Earth is the diatoms (a type of alga) that live in the sea—they make roughly one-third of the oxygen we all breathe! Plants evolved from a species of protista in the alga category, and animals evolved from a protist that was similar to a sponge-like animal.

3. **Plants**—there are over 300,000 known species, and all are producers, which means they make their own food through photosynthesis (even carnivorous plants can photosynthesize, as well). They make oxygen during photosynthesis and use carbon dioxide, are multicellular, and have cell walls made of cellulose. Plants along with algae provide most of the food and oxygen for everyone else on the planet directly or indirectly. In fact, for humans, 90% of our world's food comes from only 20 plant species! Of the 27 tons of oxygen necessary for all life on Earth, 80% is produced by algae, and 20% is produced by plants. Plants are also critical for medicine (80% comes from plants), building material, paper, clothes, clean air and water, climate, erosion and sediment control, habitat for other organisms, recreation, and aesthetics.

4. **Fungi**—most of the 100,000 known species are multicellular, although one of our favorite fungi is unicellular (yeast: important for breads, beer, wine, etc.). Fungi have cell walls of chitin, and they are usually decomposers, and some are parasites. They cannot move on their own. They are very important because they help recycle nutrients back into the soil. This kingdom boasts the largest species in the world with the "humongous fungus" in Oregon that is 3.5 miles wide and covers 2,000+ square miles!

5. **Animals**—the largest kingdom, with over 1.3 million known species (over one million of which are insects versus only about 5,500 mammals). Animals are all multicellular organisms, have no cell wall, and are consumers because they can't make their own food and must get it from an outside source. (Herbivores eat only from the plant, fungi, and/or protist groups; carnivores eat only animals; and omnivores will eat certain organisms from all four eukaryotic categories.) Animals require oxygen for

cellular processes and produce carbon dioxide in the process. They can move by using cilia, flagella, or muscle systems. There are two major groups of animals: **invertebrates** (animals without backbones make up 98% of the animal kingdom) such as annelids (worms, leeches, etc.), arthropods (insects, spiders, crustaceans, etc.), echinoderms (starfish, sea urchins, etc.), and mollusks (snails, clams, octopi, etc.), and the **vertebrates** (animals with a backbone are the remaining 2%, roughly 43,000 species) such as fish, amphibians, reptiles, birds, and mammals.

* There are really more than five kingdoms since the bacteria are divided into two kingdoms and the protista have been broken into several kingdoms, but for our purposes, we will just refer to five kingdoms to simplify things.

The Inclusive Hierarchical System of Classification

The study of biology is also about ordering the natural world from macro to micro or vice versa in order to understand connections between organisms.

Taxonomy assigns organisms a name, while, on the other hand, **phylogeny** goes beyond naming to understanding the relationships between organisms.

Carl Linnaeus developed an amazing scientific classification system in 1758 that is still used today (with slight modifications). This system of classification is hierarchical in that the taxonomic categories form groups within groups, assigned by phylogenetic relationships. Higher categories contain greater numbers of species and have broader definitions:

The major taxonomic categories used in biology are:

Kingdom;
- Phylum or Division (for plants);
  - Class;
    - Order;
      - Family;
        - Genus;
          - Species.

When I was in school I was taught a phrase to remember the order:
Kings **P**lay **C**hess **O**n **F**ine **G**lass **S**tools

Now that domains have been added, I have heard students say,
"Dumb kids play catch on freeway go splat!"

You can make up your own way of remembering the hierarchical order to classify organisms.

Some basic definitions of some of these groups that we talk about regularly:

Taxon (**taxa**)—refers to a taxonomic group at any level.

Genus—a group of species related by common descent, and the species within a genus share certain derived features.

Species—a group of organisms that can interbreed and produce fertile offspring.

Binomial name—name for a species that consists of a genus name and a species epithet.

Genus and species name are always italicized or underlined and always Latinized (i.e., *Homo sapiens* = "wise man"). Every species of organism has one and only one scientific name governed by the **International Codes of Nomenclature**. Common names are useful but sometimes confusing, especially when different languages have different common names.

Humans are Eukarya, Animalia, Chordata (subphyla vertebrata), Mammalia, Primates, Hominidae, Homo sapiens

Let's look at some of the features that put us in these taxa.

Eukarya because we have complex membrane-bound cells; **Animals** since we are all multicellular, consumers (heterotrophic by ingestions), we have no cell walls, are motile (can move), and our embryos pass through a blastula stage. **Chordata** means we share features with all the chordates, such as notochord, dorsal hollow nerve tube, postanal tail (in utero), and pharynx with gill slits (in utero), and we also have vertebra and teeth. We are **mammals** with hair, mammary glands, and three middle-ear bones (and a placenta since we're placental mammals); we are **primates** with forward-facing eyes, color vision, opposable thumbs, and many facial expressions (as opposed to some animals that have only one). **Hominids** have even more complex social organization and brain development, longer parental care, larger body and brain size, sexual dimorphism, and 32 teeth. And finally, as ***Homo sapiens*** (humans), we have great manual dexterity with extremely developed nervous and muscular systems, erect posture, a highly complex brain with sophisticated language skills, self-awareness, ability to plan for the future, etc. (Just to clarify the connection between humans, apes, and monkeys, we are not descended directly from apes or monkeys; rather, we have common ancestors.) The human–ape line diverged from the old-world monkey line 25 million years ago, and then the humans and apes diverged again five to eight million years ago. Human, chimpanzee, and bonobo DNA are all around 98% the same due to this relationship.

The Relationship Between Energy and Nutrients

Okay, now that we have a basic understanding of the species on Earth and where we fit in, let's talk about how we are related in terms of energy and nutrients.

Energy Flow—everything is related, and energy and nutrients are recycled in the process:

The ultimate source of energy is the SUN, which provides the energy for plants and other producers to make sugars (glucose) via **photosynthesis**, one of the most important biological reactions on Earth. Photosynthesis is the process by which producers make their own food by converting carbon dioxide and water into glucose with the help of the sun's energy. Another very important product of the reaction is oxygen, needed for all life on Earth.

Photosynthesis: $CO_2 + H_2O \rightarrow$ sun's energy $\rightarrow$ glucose ($C_6H_{12}O_6$) + O_2

In order for photosynthesis to occur in plants, they must take in enough water and CO_2. Water is taken in through the roots and transported through xylem to the leaves where photosynthesis occurs. The CO_2 enters the leaves through pores called **stomata**; the pores are opened and closed by cells on each side called **guard cells**. When they open, the CO_2 can come in—usually during the day when there is enough light for photosynthesis, and then they close at night. This helps to keep water in since it evaporates out when the stomata are open. Sunlight is needed to provide the energy necessary to power the reaction and is captured by pigments in the chloroplasts of the leaves. The primary pigments are chlorophyll a and b, which absorb mostly red and blue wavelengths of light and reflect green (this is why most plants are green!). The sugar made by photosynthesis in the leaves is then transported to other parts of the plant for cellular respiration and storage by another type of vascular tissue called phloem. The oxygen made by photosynthesis exits out of the stomata. This is a very simplified explanation of photosynthesis.

All Organisms Use Glucose to Synthesize Their Own Energy

Meanwhile, all organisms (including plants) use the glucose made during photosynthesis to synthesize their own energy in the biological process called **cellular respiration**. (Since producers are the only organisms that can make glucose by photosynthesis, all other organisms must get the glucose from producers one way or another.) Cellular respiration converts glucose and oxygen into carbon dioxide, water, and **adenosine triphosphate (ATP)**. ATP is an energy-storage molecule that releases energy when it is broken down into adenosine diphosphate. Every living organism performs cellular respiration in the mitochondria of their cells to create energy. Even producers need to make their own energy despite being able to use energy from the sun to synthesize their food. Energy is necessary for every living organism to run cellular processes.

Cellular respiration: **glucose** $(C_6H_{12}O_6) + O_2 \rightarrow CO_2 + H_2O + ATP$

Notice that the photosynthesis and cellular respiration equations are opposite of one another. The amount of oxygen that the producers make (roughly 27 tons per year) is almost exactly equal to the amount of oxygen that all of the organisms on Earth take in for cellular respiration. This means that the amount of oxygen in the atmosphere stays constant. (Carbon dioxide levels, however, have not stayed constant due to increased production caused by humans. The final chapter will address this issue when we cover pollution and climate change.)

CO_2 is toxic, and we can't handle TOO much water in our system either, so we need to get rid of the byproducts of cellular respiration. They both diffuse out of our cells into our circulatory system; we release CO_2 when we breathe out and release H_2O in our urine, with our breath and through our skin. (Water makes up at least 60% of our tissues, so we do need to keep a lot of water in our systems for many of our chemical reactions and to move substances around in our body.)

CO_2 is toxic because it combines with H_2O to form carbonic acid (H_2CO_3), which can then break apart to form hydrogen ions (H^+) and carbonate (HCO_3). The buildup of acids in our cells can dissolve cell membranes and cause the cellular contents to spill into the body. We have a complex system to make sure that we don't build up too much acid in our cells. (The fact that you can't hold your breath for more than a few minutes is your body's way of making sure you get rid of your CO_2!)

Cellular Respiration and Photosynthesis Are Direct Opposites

Our bodies don't make or destroy chemicals but, rather, reorganize to build different compounds or expel them. As I already pointed out, these simplified equations of **cellular respiration** and **photosynthesis** are opposite of one another—the plants need CO_2 to make their sugar, with oxygen the byproduct that we need to make our energy, and our byproduct is CO_2, which is used by plants. (They are also using CO_2 in our atmosphere created as a byproduct of the combustion of fossil fuels or the burning of vegetable matter, among other chemical processes. Carbon dioxide is also emitted from volcanoes, hot springs, and geysers and also comes from breaking down carbonate rocks.) Plants go through cellular respiration as well as photosynthesis (they are both happening simultaneously during the day). So they are making oxygen as well as carbon dioxide at the same time.

Animals can't make their own sugar, so they rely on plants as the glucose source for cellular respiration. Herbivores and omnivores eat the plants to get the energy from the starch that the plants are making via photosynthesis; other animals (carnivores and omnivores) eat other animals that have already consumed plants and are now storing the sugar as glycogen. Meanwhile, the decomposers like fungi and bacteria decompose all of the dead plant, animal, and other matter and use the sugar for cellular respiration to make energy, and, in the process, they recycle the nutrients like nitrogen and carbon to the soil to be used again by plants. Everything is interconnected. We'll look at how affecting one part of the chain of life affects others when we get to the last portion of the book and talk about ecosystems and conservation. But for now, you should know the basic equations of photosynthesis and cellular respiration.

In order to classify life on Earth and understand how different processes work, scientists have universal guidelines that they follow when researching a topic. It has taken thousands of years of curious people to have the knowledge we now have about our planet and its inhabitants, and scientists keep discovering new things every day. Here are the fundamental steps used when performing scientific research.

The Steps of the Scientific Method

1. **Observation**. Pay attention to what's going on around you. It can be on a macro- or microscopic level. Ask questions about your observations.

2. **Hypothesis**. Form a tentative explanation to your question(s), called a hypothesis (an educated guess), based on your observations. You can make predictions based on this hypothesis to be ***tested***. (If your hypothesis cannot be tested, it is not valid for a scientific investigation since you cannot prove or disprove your hypothesis.)

3. **Experiment**. Design an experiment to test your hypothesis; make sure to have enough ***replication*** and a ***control*** (something that differs from your experimental treatment by one variable).

4. **Analyze results**. See if there are statistically significant data to either accept or reject your hypothesis.

5. **Conclusion**. Provide a detailed explanation of what your data mean in terms of your hypothesis. If your hypothesis is proven to be incorrect, you can start all over again with a new hypothesis. Every experiment is helpful!

6. **Share** with the rest of your class, the scientific community, or the public at large so that others can build on the new knowledge and review your work. (Otherwise, science wouldn't move forward as fast as it does since many scientists would be researching the same topics over and over, and without peer review, the experiment might not be considered credible.)

Basic Chemistry and Organic Molecules

CHAPTER 2

OKAY, NOW THAT WE'VE COVERED SOME BASICS IN TERMS OF science in general, we're ready to dive into a little chemistry, necessary for understanding the processes going on in the human body all of the time. We'll be looking at how small particles, like ions, affect our cells, organs, and organ systems. As we near the end of our course, we'll move up to how humans as a whole affect ecosystems. Here's some vocabulary to order and define matter. We will start from the smallest particle of matter and move up from there.

HIERARCHICAL ORDER OF MATTER AND LIFE

Quark—scientists have discovered particles even smaller than subatomic particles! Quarks combine to form particles such as protons and neutrons. (There are other particles that have been discovered recently that are even smaller than a quark, but we'll start here.)

Subatomic Particles—protons (+), neutrons (neutral), and electrons (-) are within an atom.

Atom—a basic unit of matter composed of protons and neutrons inside a nucleus with electrons circling around the nucleus. The number of protons in the atom determines the ***atomic number***. The atomic number classifies the atoms into chemical elements. (So basically, different types of atoms are called elements.)

Element—consists of only one type of atom and is categorized by its atomic number. Each atom has a different number of protons. For example, hydrogen is an atom with one proton and, therefore, its atomic number is 1. Oxygen is an atom with eight protons and is number 8 on the periodic table. The periodic table tells us how many protons are in each element (**atomic number**) and the weight of the element (**atomic mass**: the weight of the protons and neutrons combined). The mass of the electrons in an atom is negligible and, therefore, is not included in the atomic mass.

Ion—a charged atom or molecule with an unequal number of protons and electrons. If there are more protons in the ion, the charge is positive; if there are more electrons, it is a negatively charged ion.

Electrolyte—ions that dissolve in water and make a substance electrically conductive. Examples are sodium (Na^+), calcium (Ca^+), chloride (Cl^-), and potassium (K^+). These are very important for biological processes like muscle contractions and nerve impulses.

Molecule—a unit made up of two or more atoms of the same or different elements (when different elements combine they are called **chemical compounds**), i.e., H_2O is two hydrogen and one oxygen.

Organelle—"little organ" = intracellular compartment surrounded by a protective membrane (i.e., mitochondria, nucleus, etc.); biological molecules form organelles.

Cell—smallest unit with the ability to live and reproduce.

Tissue—made up of cells and substances that are combined to perform a specific function.

Organ—composed of tissue combined to perform a specialized function.

Organ System—two or more organs interacting to perform particular functions.

Multicellular Organism—an individual organism made up of cells, organized as tissues, organs, and organ systems.

Species—a group of reproducing organisms that can produce fertile offspring of the same kind (i.e., ligers are not a true species since they cannot make a new liger by reproducing together—the only way to make a liger is to mate a lion and a tiger).

Population—group of organisms of the same species living in the same area.

Community—populations of different species living in the same area.

Ecosystem—the community of organisms living together and the abiotic (nonliving) factors in the environment (such as water, climate, air, and soil). Ecosystems can be small, such as the organisms and conditions in a fish tank, to very large, such as the Joshua trees in the Mojave Desert or the kelp forests off Monterey Bay.

Biome—larger in scale than ecosystems because there can be many ecosystems within one biome. The biome is classified by main vegetation types in the area, climate (amount of precipitation and temperature), and combination of organisms. The United States is very diverse with more than ten different biomes. Examples include Mediterranean vegetation (in California), semiarid deserts, montane and temperate broadleaf forests, subtropical rain and dry forests, and many freshwater and marine biomes.

Biosphere—regions of the Earth's crust, water, and atmosphere inhabited by living things (made up of different biomes).

Reviewing Basic Chemistry

Let's look at some of our chemistry terms in more detail. Hopefully, this will help you to understand how molecules come together and break apart when we're discussing different cellular processes as well as why ions and pH affect our systems as much as they do. To understand how the human body works, you need some very basic chemistry. I am definitely not a chemistry buff, so we will really only cover the very minimum that you need for future biology topics in this text.

Matter is anything that takes up space. Matter can be in the form of a solid, liquid, or gas. The units of matter are **atoms**.

Elements consist of one type of atom. Elements cannot be broken down into another type of substance. The periodic table has 118 elements although most of these elements are rare. There are only 11 main elements in living organisms: O, H, N, C, Ca, Na, K, Cl, Mg, P, and S. (There are trace amounts of other elements, but they are very minuscule.) There are only ten main elements in the Earth's crust, ocean, and atmosphere: O, Si, Al, Fe, Ca, Na, K, Mg, H, and Ti. After you take into consideration the overlapping main elements from living organisms and the environment, there are really only 15 common elements out of the 118 discovered to date. Now let's look at some properties of elements. Looking at the chart you will see helium's (He) ***atomic number*** is 2, which means that helium has two protons, and its ***atomic mass*** is 4, which is the sum of the masses of **protons** and **neutrons** (each proton or neutron has one Dalton; Helium has two of each for a mass of 4). The mass of **electrons** is so small, it's not considered in the atomic mass.

The Structure of Atoms

All atoms have the same basic structure: the atom has a nucleus with protons and neutrons in the center, and electrons orbit the nucleus. The protons have a positive charge, and if it has neutrons (which are neutral), they are in a 1:1 ratio. The only element without any neutrons is hydrogen (the atomic mass of H is only 1). If the neutrons are not in the same proportion as the proton (can be more or less), it is called an **isotope**. For example, regular carbon has six protons and six neutrons, but the isotope carbon-14 has six protons and eight neutrons. Many elements have isotopes, with the same number of protons but a different number of neutrons. All isotopes of a particular element are chemically identical but have different masses.

Tiny electrons (negative charge) orbit the nucleus at high speeds in **valence shells**. Atoms have an equal number of protons and electrons and, therefore, are neutral. If an atom gains or loses an electron, it becomes a charged atom called an **ion**, which has a charge corresponding to the number of electrons lost or gained. Electrons are lost or gained from the atom's outer valence shell. Atoms with many electrons have multiple valence shells, and each shell can hold a limited number of electrons in the outer shell. The first shell can hold two electrons, maximum; all of the following shells (second shell, third shell, fouth shell, etc.) can hold up to eight electrons in the outer shell. (However, starting with the third valence level, shells inside the outer shell can start building up more than eight electrons, but the outside shell will never have more than eight electrons.)

Chemical properties of an atom depend on the number of electrons in the outermost shell, and an atom is stable if the outer shell is complete. Atoms with a filled outer shell are **inert** or unreactive elements and are called **rare** or **noble gases** (they are on the right edge of the periodic table). These atoms with no "vacancies" usually don't take part in chemical reactions. Other elements with their outer shells missing electrons can share, gain, or lose electrons to achieve the stability of a filled outer valence. Elements that have either one or seven electrons in the outer valence shell are particularly reactive (which we will see when we discuss sodium chloride).

How Do Elements React and Bond?

There are different ways elements react and bond with one another. These interactions result in atoms staying together to form **molecules** through these chemical bonds. Molecules can be the same or different atoms joined together. When elements combine to form substances consisting of two or more different elements, they are called **chemical compounds,** such as water (H_2O). Compounds consist of two or more elements in proportions that never vary; for example, every H_2O molecule compound has one oxygen atom bonded with two H atoms.

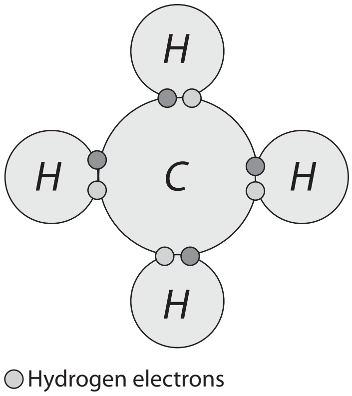
There are four elements that make up 96% of the chemical composition of living matter: **carbon**, **oxygen**, **hydrogen**, and **nitrogen**. There are small quantities of other elements in humans, as well, such as calcium, phosphorus, sulfur, sodium, chlorine, magnesium, and trace elements such as iron, iodine, and selenium, but we are going to concentrate on the four main elements since they make up the bulk of our bodies. We are composed of about 60% to 75% H_2O, and the other "dry weight" is mostly organic building blocks such as proteins, carbohydrates, lipids, and nucleic acids. We will discuss these more in depth at the end of this chapter, but for now, let's look at some of the ways the elements are bonded together to form these molecules in our bodies.

Covalent Bonds

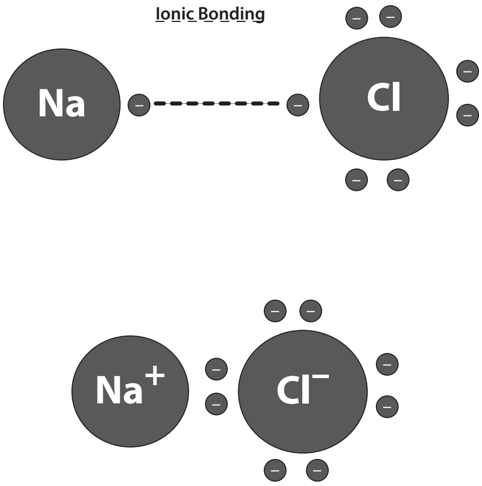
Sharing at least one pair of electrons is known as **covalent bonding**; for example, H-H (H_2) uses a single covalent bond (sharing one pair of electrons). Two oxygen atoms (O_2) are bonded together with a double covalent bond (O = O), which means that they share two pairs of electrons. This is an even stronger bond than a single covalent bond. (The more pairs of electrons shared, the more stable the bond becomes.) Covalent compounds are usually liquids or gases at room temperature, like H, N, O, and all of the halogens (the row to the left of the noble gases—F, Cl, Br, I, At, Uus). Covalent bonds are found in CO_2, O_2, H_2O, and glucose, all critical for the human body.

Ionic Bonds

Atoms with unfilled orbitals in their outermost shell tend to interact with other unstable atoms; as I said before, there are different ways they can interact. We just covered sharing of electrons; another way is by transferring electrons from one atom to another. **Ionic bonds** form when electrons are transferred from one element to another, and the elements become ions (charged atoms). Opposite ions attract to form ionic bonds. Sodium chloride is an example of a chemical compound held together by an ionic bond. Sodium (Na) has 11 protons and 11 electrons (the outer valence shell has one electron). When Na associates with chlorine (Cl), which has 17 protons and 17 electrons (with seven electrons in the outer valence shell), the Cl, which is more electronegative, strips one electron away from the sodium turning it into a positive ion (cation) (Na^+). The extra electron on the Cl makes it into a negative ion (anion) (Cl-), and the opposites attract and make NaCl with an ionic bond—a very weak bond that can be dissolved in water. (NaCl, sodium chloride, is also known as table salt, which is made up of thousands of sodium and chloride elements ionically bonded together to form salt crystals.) Molecules formed by ionic bonds are, generally, all solids at room temperature as opposed to covalent bonds, which can be gases, liquids, or solids.



The elements in this molecule of CH4 are held together by covalent bonds.



Hydrogen Bonds

Other weak bonds are **hydrogen bonds**, also vital to biology. There is a slight positive charge on hydrogen atoms that are covalently bonded to a more electronegative element, and this slight charge can form weak attractive bonds with adjacent slightly negative atoms. The hydrogen bond is much weaker than covalent or ionic bonds, but it does cause attractions between nearby molecules. Hydrogen bonds exist in all life forms since they are the bonds that join two strands of DNA together in the double helix configuration. The bonds are easily broken during DNA replication and then are formed again once the process is completed. The bonds are also present in joining water molecules together as well as forming the shapes of protein molecules.

Explaining Chemical Reactions

Bonds do more than just hold elements/molecules together; some store energy when bonds are formed (like in the case of making sugars), and these are called **endothermic reactions**. Other bonds release energy (**exothermic reaction**) when molecules are broken apart. In an exothermic reaction, energy is released when the bond is broken.

Chemical reactions involve making or breaking chemical bonds and, thus, changing the composition of matter. Enzymes (which are proteins) help to speed up the rate of reactions.

Example: $H_2O_2 \rightarrow H_2O + O$ using peroxidase (enzyme)

In this example, the ***substrate*** hydrogen peroxide (H_2O_2), which is toxic, is converted to the non-toxic ***products,*** water and oxygen, with the help of the ***enzyme*** peroxidase. Chemical reactions like this are occurring in our bodies all the time. Usually, an endothermic reaction is coupled with an exothermic reaction so that energy (in the form of ATP) is released from the exothermic reaction to run the endothermic reaction. Reactions can occur without enzymes, as well, but they would take a lot longer. We will go over enzymes in more detail when we talk about proteins.

Water, the Most Important Molecule on Earth

Water is the most abundant and important molecule on Earth (the Earth is 73% water) as well as in living organisms. It makes up between 60 and 75 percent of total body weight in animals (more for certain animals like jellyfish!) and even more for plants—up to ~98% for some plants! Humans are composed of about 70% water. Our bodies need water to perform many basic functions like digestion, excretion, respiration, and circulation. Without enough water, the body becomes dehydrated, chemical reactions fail, and cells die. Too much water can cause our body to fail, as well, and we will talk more about this when we discuss the urinary system, which helps control our water balance. Water helps to keep our body within a livable pH range, too. Our blood is mostly water and remains close to neutral with a pH of 7.4. If the blood becomes too acidic or basic, we can die, so it's important for our body to constantly monitor and make adjustments when necessary to maintain homeostasis. An ***acid*** is a substance that produces hydrogen ions (H^+) in water, and a ***base*** is a substance that produces hydroxide ions (OH^-) in water. Measuring the concentration of hydrogen ions in a solution gives you the amount of **potential hydrogen**, also known as **pH**. The pH scale goes from 0 to 14, and anything under 7 is acidic, 7 is neutral, and above 7 is basic. Most of our biological fluids are between 6 and 8 on the pH scale with a few exceptions. (For example, the gastric juice in the stomach is closer to 2, which is important for digestion and fighting pathogens that might enter with our food.)

The Four Main Organic Macromolecules

Water is critical for chemical reactions, as well. Water helps to build and break apart **organic molecules**, which make up the remaining 30% of the body weight in living organisms. ***Organic*** refers to molecules that contain carbon. Most organic molecules also contain at least one hydrogen atom. The **four main organic macromolecules** in all living things are **carbohydrates**, **proteins**, **lipids**, and **nucleic acids**. Many of these organic molecules have the carbon and hydrogen linked in hydrocarbon chains, which are very stable structures. These chains can also have a functional group attached made up of particular atoms or clusters of atoms that are covalently bonded to carbon and can influence the chemical behavior of the macromolecule. One unit of macromolecule is a monomer; three or more monomers are a polymer. Water can be taken away or inserted into macromolecules in order to make or break molecules. These two very important opposite reactions are constantly occurring in our cells.

Joining Molecules or Breaking Them Apart

Dehydration synthesis occurs when enzymes remove a hydroxyl (OH) from one molecule and a hydrogen atom (H) from another molecule, and the two molecules are then joined by a covalent bond (where the OH and H used to be), and the discarded OH and H form H_2O. (This is also called a ***condensation reaction***.) This is a common building reaction to make molecules.

In order to break molecules apart, the opposite occurs: enzymes split molecules into two or more parts and then attach an OH group and an H atom from a molecule of H_2O to the exposed sites. Adding water helps break apart large polymers into smaller units, which can be used for building blocks (to make other macromolecules) or to make energy (ATP). This reaction of breaking molecules apart is called **hydrolysis**.