The Processes of Life

An Introduction to Molecular Biology

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1 In the Beginning . . .

1.1 Approaching the Study of Life

Questions about the origin, functioning, and structures of living things have been pursued by nearly all cultures throughout history. The work of the last two generations has been particularly fruitful, producing a remarkably detailed understanding of how living things operate. This new understanding is grounded in physics and, especially, in chemistry. Insights into the molecules of life have clearly demonstrated how fundamentally ordinary materials can be alive in so many extraordinary ways.

Becoming conversant with the intricacies of molecular biology and its extensive technical vocabulary appears a daunting prospect. Introductory textbooks typically run more than a thousand pages, and college courses in the field can require years of prerequisites. As more and more people become seriously interested in molecular biology, the existing introductory materials too often form more of a barrier to entry than an invitation to the study of life. This book is an attempt to open that door for anyone who wishes to enter.

It's not that molecular biology is more difficult than, say, physics or chemistry, but that the study of life at the molecular level involves so many interconnected strands of knowledge that it is hard to find a good place to start. Life is frustratingly holistic. Studying one organ in isolation from the rest of the body, or even one organism in isolation from all the others, doesn't work well. How is it possible to learn about all of them at once?

Learning molecular biology is like climbing a spiral staircase: one goes around and around a set of core topics (reproduction, evolution, development and so on), each time a topic is revisited, one reaches a higher, more complete understanding. The purpose of this book is to take you around that spiral once, so you are ready to appreciate more detailed knowledge about any aspect you care to pursue further, be it how DNA works or how to treat cancer. A spiral is an imperfect metaphor, since there are so many linkages among biological concepts—for example, how DNA works and treating cancer turn out to be related. It is simply impossible to lay out biology linearly, so this book is laced with cross-references, to help you navigate the connections that didn't fit exactly into the path I chose to get you around the first level of the spiral.

What does it take to go around that spiral once? What are the core topics for understanding life? From at least the days of the early Greeks, humanity has searched for a "substance of life," a special material that was the essence of living things. The search for that special substance turned out to be a mistaken conception of what life is. While some materials (like DNA and proteins) are found in nearly all living things, it is not a special kind of stuff that makes something alive. The mere presence of any particular material (including DNA) doesn't make something alive. The materials of life, it turns out, are just fairly ordinary chemicals, in particular combinations. What makes something alive is not what it *is*, but what it *does*. The *substance* of life is less important than the *process* of life.

To get around one loop of the spiral, you will have to start picking up the terminology of biology, which is a bit like learning a foreign language. The things that molecular biologists talk about don't have a lot of equivalents in the everyday world, so they invented words to describe what they discovered. Learning that language is part of what it takes to understand molecular biology. This book is filled with the technical terms you will need to know to understand other biological texts, each introduced with enough context to make sense. All of these terms are defined in the glossary and **boldfaced** at their first occurrence in the text.

Learning a foreign language involves more than just learning its words and grammar; a language embodies many aspects of its speakers' culture. The same holds true for the language of biology. The culture of biology is different from that of physics or engineering. Biologists conceive of experiments and data in their own ways, and think about the phenomena they study "biologically." Though it is difficult to describe any culture briefly in words, perhaps the most central idea in the culture of biology is the interplay of **structure** and **function**. Structure, to a biologist, describes the details of the physical components of a living system and how they relate to each other; it is what a thing is. A structure can be as complex as an organ (like the brain), or as basic as the shape of a molecule. Function, to a biologist, is the role that a structure plays in the processes of life—what a thing does. Much of what biologists do is to identify the structures that make possible a function, or to identify the function that some structure serves.

Another key aspect of biological culture is its obsession with the particular. Many other kinds of science focus on finding very general rules or laws that describe the behavior of a large part of the universe. Through hard experience, biologists have discovered that there are very few universals in biology. Even some of the most widespread phenomena in life (such as the use of DNA to encode information) turn out not to be quite universal; a few organisms always seem to manage to do things differently. For that reason, biologists are wary of generalizations.

Physicists have long derided biology's lack of generalizing theory. The Nobel prize–winning physicist Ernest Rutherford famously dismissed biology as "mere stamp collecting." He meant that biologists' scientific work has largely been to describe the phenomena of life, in exacting detail. For many years, biological science largely entailed painstakingly cataloging the tiny differences between thousands of kinds of creatures, noting exactly what their bodies look like, how they behave, what they eat, how they reproduce, etc. Physics didn't go around cataloging how different kinds of matter move, but instead created predictive theories of various kinds of motion. In a way, Rutherford was right: There isn't a grand theory of biology that can predict how a robin gets its food, or how yeast reproduce, and there probably never will be.

However, perhaps a better metaphor for the work of those biologists might be collecting biographies, not stamps. Imagine that you wanted to understand what it meant to be human. No matter how well you understood one person, that could not possibly be enough to understand humanity. Learning in detail about a lot of different people's lives, say, by reading many biographies, begins to show something of commonalities and the differences among people, and provides a basis for an understanding of what it is to be human. Different people's lives illuminate different aspects of our shared humanity. No simple theory can provide the same richness of detail, the same fidelity to the essential complexity. This also holds true for our understanding living things. At many points throughout this book, I present a bit of the life story of an organism that illustrates a specific aspect of how life works.

Why collect biographies? Because human beings are different. Why describe so many different organisms in such detail? Because living things are even more different. Life encompasses a tremendously broad range of organisms. There are so many organisms of so many different kinds that it is hard to imagine. The vast majority of organisms in the world are completely outside most people's experience, since they are too small to be seen with the naked eye and live only in a very narrow range of places. The plants and animals with which most people are familiar, diverse as they may be, are really just a tiny fraction of the enormous number of living things currently alive and an even smaller fraction of the life that has ever existed on Earth.

The question of what, exactly, is alive is itself a challenge. No precise definition of "life" is accepted by all scientists as correct. Even the **cell**, the structure that (almost) all living things are made from isn't quite universal: Viruses aren't made of cells.[1] Cells are somewhat circularly defined as the simplest entity that can exist as an independent living system, and they are the basic structural component of all organisms. Many organisms are just a single cell. Human beings are made of more than 100,000,000,000 of them.

However, speaking more informally, it isn't hard to describe some of the essential processes something must do in order to be considered alive. A living thing must **reproduce**, that is, to have the ability to create other organisms (although sterile animals, like mules, are still considered alive even if they cannot reproduce). Questions about reproduction in all its forms, from the functioning of cell division to how the genetic combination of two adults can create a child, are a central topic of biology.

A living thing must also have a **metabolism**, that is, to be able to convert external materials into its own components, or into offspring (although viruses don't have their own metabolism; they hijack the metabolism of other living things to make their components and offspring). Metabolism is a remarkable process. Some organisms, called **autotrophs**, need only inorganic substances (usually carbon dioxide and ammonia) and sunlight or another source of energy to make all of their own components. Some plants and many single-celled organisms are autotrophs. All other creatures are **heterotrophs**, which means they have to consume materials created by other organisms (usually by eating them) to get all the inputs they need to live. All animals, including people, are heterotrophs. We will see how organisms are able to take only available inputs and use them to synthesize the many complex substances—in just the right amounts and organized in just the right way—to create or sustain a living thing, using only ordinary chemistry and physics.

We will explore these and other processes, but the most basic one, the one thing that really does link all living things without exception, is **evolution**. As the remarkable nineteenth-century Jesuit priest and paleontologist Pierre Teilhard de Chardin put it, "Evolution is a light which illuminates all facts." The entire study of life, from biochemistry to ecosystems, hinges on evolutionary explanations.

What is "evolution," anyway? It isn't a particular "theory"; there are many competing theories about how evolution works. Evolution is a kind of process, a way that a particular kind of change occurs. We will look at it in detail in

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[1] Viruses do have to infect a cell in order to reproduce.

the next chapter, but one of the most critical ideas shared by all theories of evolution is both remarkable and easy to understand: all living things are related to each other. All living things have a common ancestor; somewhere, way back when, every creature has a great-great-great-great- . . . -great grandparent in common with every other creature. Human beings are distant cousins to dinosaurs, and to bacteria; sometime, long ago, we have a common ancestor with both. That's one reason that no one organism can be effectively studied in isolation.

To understand any member of the great family of life, it will help to know about some of the relatives. We will shortly take a look at the diversity of life on Earth, and also the history of living things, before diving into any particular organism in detail.

1.2 Billions and Billions of Creatures . . .

To understand biology, even molecular biology, requires an appreciation of the diversity of living things. There is a tremendous range of differences—in what they look like, how they live, how big they are, where they live, how they eat, how they reproduce, how long they live, what they can sense, what they can do, what they can think, and more. There is variation among species, among individuals within a species, among the parts of an individual organism. From the molecules up to the ecosystems, there is tremendous diversity and tremendous variability.

Let's consider a few illustrative examples. Most people looking at an aspen grove see a bunch of separate trees, but it is really a single organism, connected together by a single root system, sharing nutrients and reproducing as a unit. Figure 1.1 shows an aspen grove in Utah, nicknamed Pando, that is generally considered to be the largest organism in the world. It covers more than 100 acres and includes more than 47,000 stems (which look like individual trees). Pando is estimated to weigh more than 6,500 tons, and is likely to be at least 80,000 years old. In contrast, consider the much smaller critter in figure 1.2, named radiodurans. It is an example of a large family of organisms called the *Archaea*, a microscopic form of life that wasn't even suspected to exist 30 years ago.[2] Archaea live in all sorts of environments that were previously thought to be impossible for living things to survive in, like in acid so strong it can dissolve steel, or in superheated, high-pressure volcanic vents at the bottom of the ocean. The radiodurans in figure 1.2 gets its name from its

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[2] Before then, the few that were known were thought to be a kind of bacteria. In fact, despite their small size, they are more closely related to people than they are to bacteria.

Figure 1.1
An Aspen grove. While it appears to be a forest of trees, actually all of the stems visible here are part of the same organism.

amazing ability to survive 100,000 times the radiation that would kill a person. It can also survive being totally dried out—when there is enough water to rehydrate it, it comes back to life. These creatures that survive in such weird places are called *extremophiles* and there are many kinds of them.

There are other kinds of extremes in life as well. Consider the mayfly in figure 1.3. The lifespan of a mayfly is about two weeks, but most of that is spent in a juvenile stage, growing up. Their entire adulthood lasts only about five minutes. In that five minutes, they find a partner, mate, lay eggs, and die.

At the other end of the longevity spectrum is the desert tortoise, seen in figure 1.4. They can live to be over 120 years old; there's one in an Australian zoo claimed to be 177 years old. They may live even longer than that; it's hard to tell when the recordkeepers don't live nearly as long as the tortoises do. The age at which a tortoise reaches adulthood depends on the availability of water, and can range anywhere between 12 and 20 years. Not only do they live a long time, modern turtles have been around in much the same form as they are now for more than 200 million years, more than one hundred

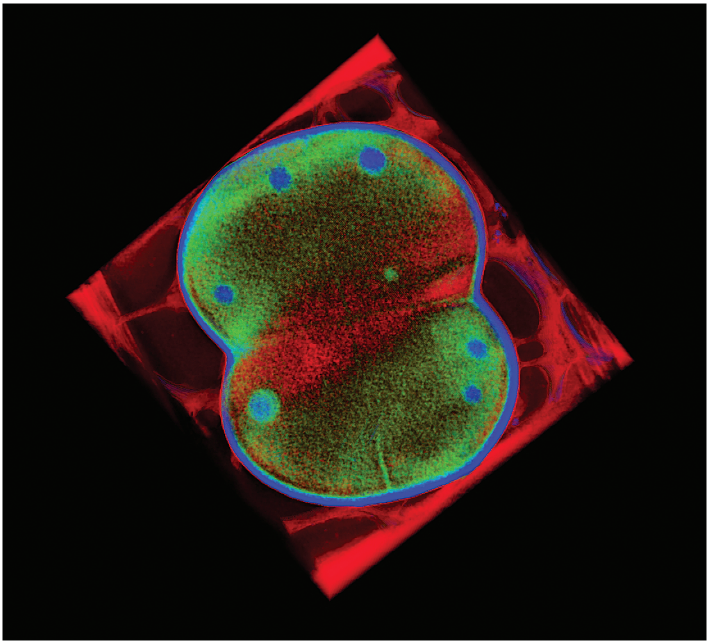

Figure 1.2
Visualization of Cryo-EM tomographic reconstructions of frozen-hydrated *Deinococus radiodurans*. Image courtesy Cristina Siegerist of the U.S. Lawrence Livermore National Laboratory.

times longer than humans. Turtles were there in the very early days of the dinosaurs.

Opabinia, shown in figure 1.5, is a very ancient creature that lived in the Cambrian era, about 500 million years ago, long before dinosaurs. The model in the figure is based on a fossil found in the Burgess shale in the Canadian Rockies, where many beautifully preserved and very ancient creatures were discovered. Opabinia has five eyes and about a third of its body looks like a long flexible tube with teeth at the end. There's nothing at all like it in the modern world, and its fossils demonstrate that there's nothing "universal" about the way life looks now.

These are just a few of the examples of the huge number of species on the planet. How many species are there? It may seem odd, but no one knows exactly. There is some controversy over exactly what should constitute a species. The original definition, attributed to the great biologist Ernst Mayr, is a group of potentially interbreeding organisms that are reproductively isolated from other such groups. However, that makes it difficult to determine species boundaries in organisms that don't reproduce sexually (e.g., bacteria), and the

Figure 1.3
A Mayfly on a white painted board. The fly stands with its wings raised, the black veins in the wings clearly visible. It has three long hairs protruding from the back of its segmented abdomen. This photo was submitted to Free Nature Pictures, http://www.freenaturepictures.com, by Rickard Olsson, with reprint permission under the Creative Commons License.

question of which organisms are "potentially interbreeding" can be hard to answer. We can say with certainty how many species are known[3] and described, and can make some good estimates of lower bounds for other sorts of species. For example, there are 5,416 known species of mammals, 9,934 species of birds, and at least 29,300 species of fish. But those are the familiar and most studied sorts of organisms. Most of the biodiversity in the world is in less familiar organisms. For example, there are at least 258,650 kinds of flowering plants, and 950,000 species of insects. Estimating the number of bacterial **taxa**[4] is extremely difficult. More than 18,000 pure strains are available from the American Type Culture Collection in Maryland, but these are just a

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[3] One reliable source for species counts, used here, is the International Union for Conservation of Nature and Natural Resources "redlist," http://www.iucnredlist.org/info/tables/table1.

[4] Taxa (singular taxon) are groupings of organisms. The idea is similar to species, but more generic. Since exactly what would count as a bacterial species is unclear, I use "taxon" instead. How many there are is still an open topic; see, for example, Thomas Curtis's article "Estimating prokaryotic diversity and its limits," in the *Proceedings of the National Academy of Science*, 99;16 (2002, Aug 6):10494–9, available at http://www.pnas.org/cgi/reprint/142680199v1.

Figure 1.4
A Mohave Desert Tortoise. This is from the U.S. Fish and Wildlife Service, and was taken by Jeff Servoss.

tiny fraction of what can be found in the world. Recent estimates suggest there are many millions of kinds of bacteria (see suggested readings at the end of this chapter), most of which have yet to be studied at all. While no one is sure, there are probably even more kinds of viruses. Viruses are obligatory **parasites**, since they depend on another creature to reproduce. Every organism also appears to have its own set of viruses, as well. Even bacteria get viruses.

How to make sense of all this diversity? That question is as old as human investigation of the living world. Aristotle was among the first to try to organize living things into categories, that is, to develop a taxonomy of life. In the mid-1700s, Carl Linneaus devised the first hierarchical taxonomy based on observable characteristics, and devised a nomenclature (naming system) for living things that largely persists to this day. The scientific name of an organism has two parts, a **genus** (which names a group of related organisms) and a **species** (which identifies a particular member of the group). For example *Homo sapiens*, the scientific name for people, indicates that we are part of the group of related organisms called *Homo* (which include *Homo neanderthalensis*, our

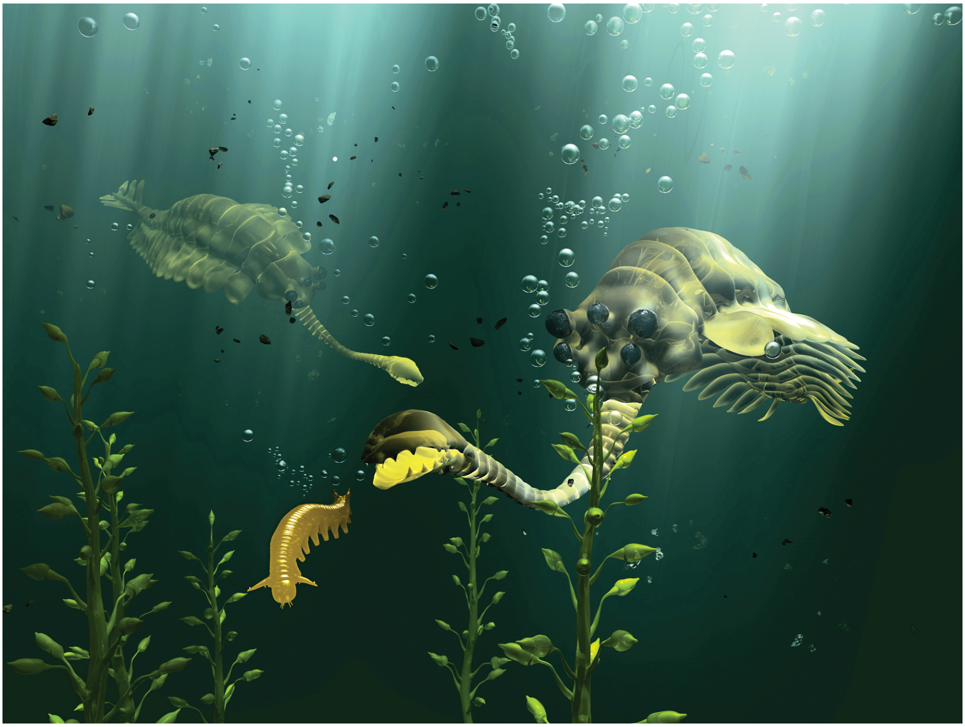

Figure 1.5
An imaginary reconstruction of an Opabinia by Olof Helje used by his permission.

extinct relative, popularly called the Neanderthal). Sometimes the genus is abbreviated by its initial letter, as in *H. sapiens*.

There is a much more extensive hierarchy of groupings as well. For example, species in the genus *Homo* are all kinds of primates, which are in turn all kinds of mammals, and so on. Since all of these organisms are related to each other, it is possible to construct a family tree that visually illustrates the groupings and the splits that have occurred. The most basic (and most ancient) split created three very broad divisions: the Bacteria, which are simple, single-celled organisms; the Archaea, which are more complex single-celled organisms containing the extremophiles mentioned previously; and the **Eukaryotes**, which include all plants and animals, and many other organisms as well. Even in the most familiar class of animals, the vertebrates, there are many unfamiliar creatures with a great deal of diversity in aspects such as body plan, environmental niche, and lifestyle. So many organisms are now known that it is impossible to print even a summary of the tree on a single page. An animated tree that is well worth exploring can be found on the wonderful "Understanding Evolution" Web site, http://evolution.berkeley.edu.

1.3 . . . All Alike!

There are more than a million kinds of organisms, each with its own special, defining characteristics: different sizes, shapes, lifespans, ways of eating, ways of reproducing, ways of sensing and acting. How is it possible to make sense of all of this diversity, other than just collecting all the "biographies"? Perhaps the most remarkable discovery in the history of biology is that the molecular processing that goes on in all of these creatures is remarkably alike.

The two most critical functions that living things have to achieve are (1) managing matter and energy so as to stay alive, and (2) creating offspring. The molecular structures that underlie those two basic functions are quite similar in all of these different organisms. This surprisingly uniform set of molecular mechanisms is strong evidence that all living things do, in fact, have a common ancestor, and it is also the reason that so much of biology has become oriented around molecular studies.

The molecules that do all the work of being alive fall into a few, well-defined categories. The first is a set of very large and complex molecules called **proteins**. Proteins, working together in groups, are directly responsible for most of the remarkable things that living things can do, reshaping matter and energy to sustain life and create offspring. Each organism uses thousands of different proteins to go about its life. The ability of radiodurans to survive so much radiation, or of aspen groves to get energy from the sun, each depends on the activity of thousands of particular proteins.

Proteins are interesting molecules, and later we will examine their structure and function in some detail. There are millions of kinds of proteins in the world. The bacterium *Synechococcus elongatus*, a relatively simple autotroph, needs about 2,500 proteins to do its work. Very complex organisms might make 100,000 different proteins, many of which are modest variants of each other. Each protein (a structure) can accomplish a specific function (or sometimes more than one). Proteins can be studied in isolation, but they usually work in groups. A useful metaphor for proteins is as basic commands in a computer programming language; they can be combined in various ways to define all different sorts of processes.

Proteins are very powerful and complex molecules, but they actually have a simple underlying structure: they are **linear polymers**. A polymer is a chemical compound made up of simpler units (called **monomers**) that are repeated many times, like LEGO®[5] blocks. The simple units in proteins are **amino acids**. Most organisms have about 20 different kinds of these pieces. The fact that proteins are linear polymers just means that the parts form no branches or circles: a protein can be thought of as a simple "chain" of amino acid "links." Every protein can be described by enumerating, in order, the amino acids that make up its chain, called the protein's **sequence**. Most proteins contain between 100 and 1,000 amino acids. Protein chains are flexible, and the details of their sequences determine a characteristic three-dimensional shape that each protein folds up into. As described in detail in section 5.1, the particular details of the sequence of amino acids and the resulting folded shape is what gives each protein its unique functional capabilities.

Figure 1.6 shows two representative proteins.[6] Figure 1.6a shows a molecular rendering of part of the protein collagen. Collagen is the most prevalent protein in human beings, making up nearly a quarter of all the protein in your body. It forms strong sheets and cables that support skin, internal organs and tendons, as well as the hard substance that gives shape to the nose and ears. Collagen is a braid of three nearly identical protein chains, each more than 1,400 amino acids long. It is one of the largest proteins in the body. However, this very long chain is made up mostly of the same three amino acids, repeating over and over again. Each of the three amino acids is given a different color in the image, and on one of the chains, the atoms that make up each amino acid are shown as little points. The other protein in figure 1.6b is insulin, one of the smallest proteins in the body, consisting of only 51 amino acids. Insulin is a special kind of protein called a **hormone**. Hormones function as messages, sent from one part of the body to another through the blood, and insulin is one of the most important of those. Its message is about how much sugar is available in the blood, and it plays an important role in managing energy. Insulin, like most other proteins, forms a compact, ball-like shape, called **globular**; collagen is unusual in its extended rodlike shape.

Another important family of molecules common to all living things are the **nucleic acids**, **DNA** (**deoxyribonucleic acid**) and **RNA** (**ribonucleic acid**). The nucleic acids are also linear polymers, although their components are **nucleotides**, not amino acids. There are only four different nucleotides (in

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[5] LEGO® is a trademark of the LEGO Group of companies.

[6] Note that the images in both figures 1.6 and 1.7, and, for that matter, any image of a molecule, are really just useful fictions created to help us understand. There are many illustrative ways to portray the structure of molecules, but none is an actual image of a molecule. In figure 1.6a, the molecules are rendered schematically, showing only a few atoms. In figure 1.6b, the schematic molecule illustrates only the bonds between the atoms. In figure 1.7, the atoms are represented as little balls stacked on top of each other. These and other renditions of molecules are described in more detail in section 5.1.1.

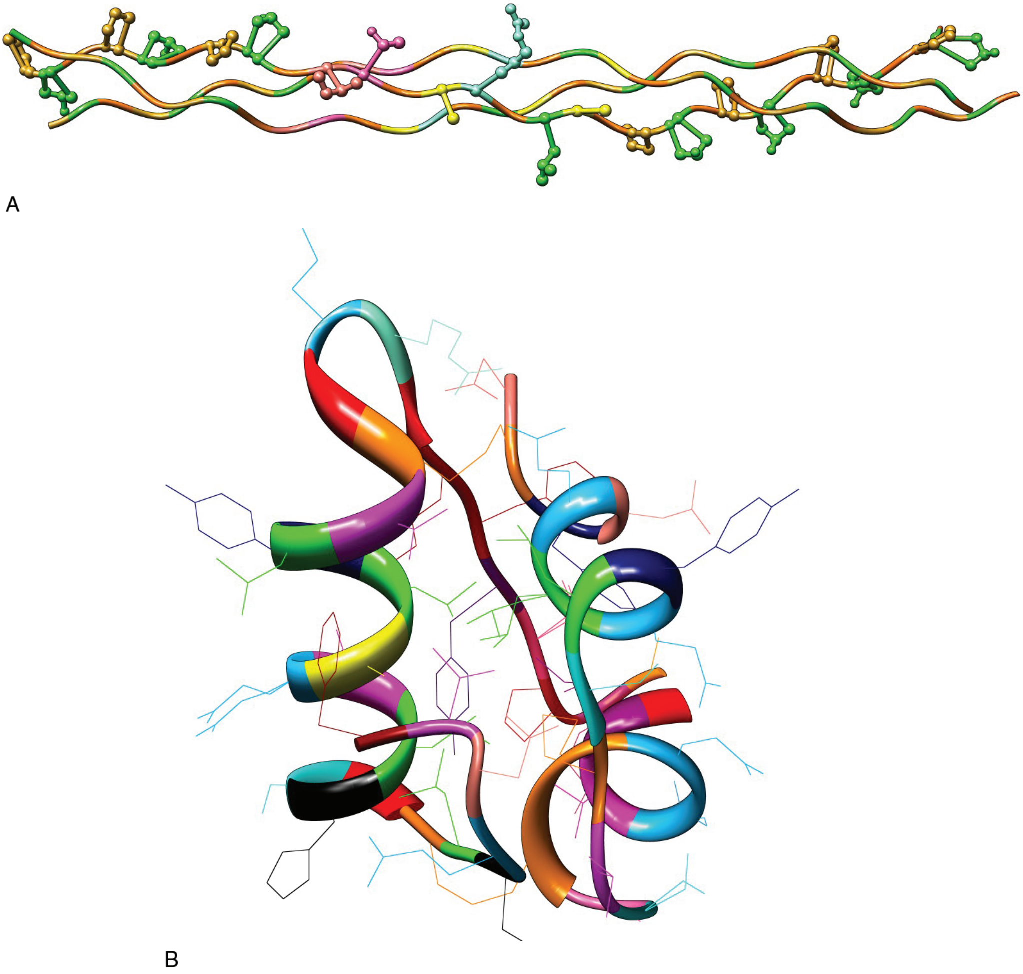

Figure 1.6
Molecular renderings of two proteins. Panel (A) shows a small portion of the protein collagen, which is a long braid of three nearly identical strands. Panel (B) shows a rendition of a complete insulin protein, one of the smallest proteins found in nature. Section 3.1.2 discusses how to interpret these molecular renditions.

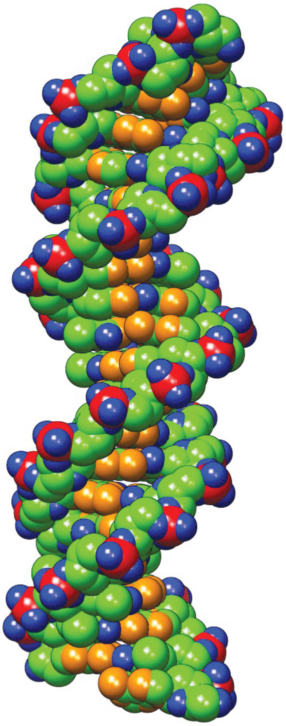

Figure 1.7
A short stretch of a DNA molecule. The green balls represent carbon atoms, the blue represent nitrogen, the red oxygen, and the orange phosphorus. The hydrogen atoms are not shown.

contrast to the 20 or so amino acids). Also unlike proteins, DNA doesn't fold up into different shapes depending on its sequence. Most of the time it forms the well-known "double helix" shape, shown in figure 1.7.

DNA's function is to encode information. More specifically, it encodes all of the sequences of all of the proteins that an organism needs to live. There is a translation between a sequence of nucleotides in a DNA molecule and the sequence of amino acids in a protein. One interesting thing about DNA is that a single molecule of it encodes all of the information necessary to produce thousands of proteins. For that reason, DNA is an extremely long polymer. Some DNA molecules contain more than two hundred million (200,000,000) nucleotides. If you could take one of the DNA molecules in your body and stretch it out straight, it would be nearly three inches long. That is a very long molecule! [The single molecule would be only about 0.000001 of an inch wide, though.]

DNA, RNA, and proteins together are called **macromolecules**. “Macro” means big, since all of those molecules are quite large compared to most compounds that are not produced by living things. In contrast, biologists call all of the other substances involved in life (e.g., sugars, vitamins, oxygen, pharmaceuticals, etc.) **small molecules**. The universality of the structures and functions of the macromolecules, the fact that every living thing uses nucleic acids to encode information and proteins to do biochemical work, is remarkable, considering the diversity in the world of living things. This commonality is what has made possible the advances in understanding life that the past few generations have witnessed.

Molecular biology began with the insight by James Watson and Francis Crick (and also Rosalind Franklin[7]) that DNA was the carrier of the information needed to make all of the proteins in the body. They formulated what is now called the “central dogma” of molecular biology: Information about how to make proteins is encoded in DNA. DNA can be copied to make more DNA, copying all the information in the original. The information in DNA can be transcribed into RNA, which then directs the production of a protein whose sequence of amino acids is determined by the sequence of nucleotides in the DNA (and RNA). The information flow is always either DNA to DNA or DNA to RNA to protein. No other information flow (say, using the information in a protein to create DNA) is possible.

While it is a revolutionary and important way of looking at living things, even the central dogma has a few exceptions. In biology, there are always a few exceptions. In this case, one exception is a family of viruses that actually keeps its protein codes in RNA, and copies information from RNA into DNA, which then directs the host to produce viral proteins and more viral RNA. Since these viruses run the normal process backwards, they are called “retroviruses.” HIV, the virus that causes AIDS, is a retrovirus. The retrovirus’ ability to use RNA to insert a sequence into DNA turns out to be a useful mechanism in the laboratory, so the mechanism used to accomplish that is now commonly used by scientists and engineers as well (see section 10.3).

The DNA in an organism (RNA for retroviruses) contains all of the information necessary to make an offspring.[8] For that reason, the complete sequence of all of the DNA in an organism can be said to encode its entire heritage. The technical ability to “read” DNA sequences has advanced greatly, and it is now

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[7] See “Rosalind Franklin and the Double Helix” *Physics Today* (March 2003): 61. Available as http://www.physicstoday.org/vol-56/iss-3/p42.html.

[8] The proteins in the egg also play a role in the process, but a relatively modest one. The process is discussed in more detail in section 7.2.

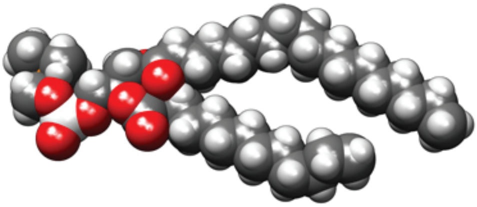

Figure 1.8
Phosphatidylcholine, a lipid molecule. The white balls represent hydrogen, the gray carbon, and the red oxygen.

practical to determine the sequence of all of the DNA in an organism. This process is called **genome sequencing**. As will become clearer as this book unfolds, knowing this sequence is very valuable, but we are still a long way from understanding the meaning of all the information that it encodes.

Finally, we will also explore some biologically important small molecules. Perhaps the most important class are the **lipids**, including that most familiar lipid, fat. Lipids are polymers, but they are not linear; sometimes they form branches, as shown in figure 1.8. Lipids play many important roles, including forming the membranes that define the “skin” of individual cells, signaling important messages from one part of the body to another, and providing for the storage of energy. Other important small molecules include sugars, starches, and a ubiquitous compound called ATP (adenosine triphosphate), which is one of the main molecules involved in the distribution of energy.

1.4 Where To from Here

Now we have the concepts to at least say what molecular biology is: the study of the structure and function of biological molecules, large and small. Though the differences among organisms are important, it is now possible to explore the underlying similarities that unite all of life: its molecular mechanisms. The process of life is an elaborate dance of interacting molecules.

To really understand the functioning of those molecules requires looking beyond just the molecular. We start in chapter 2 by looking at the process of evolution, the process that gave rise to both the unity and the diversity of life. Chapter 3 describes just enough chemistry to appreciate the amazing things that organisms are able to do with matter and energy. Building on that foundation of evolution and chemistry, chapter 4 describes the universal processes found in even the simplest life forms, and introduces some of the molecular structures that underlie those functions. Chapter 5 returns to the biological macromolecules, proteins and nucleic acids, explaining in more detail how they carry out the processes of life. Chapter 6 introduces the more complicated structures and processes of the eukaryotes, the branch of life that includes all plants and animals. This chapter covers some of the more familiar—but not universal—processes of life, such as breathing oxygen or having sex. In chapter 7, we consider the complications in making a multicellular organism, including cellular specialization, development, and the molecules that coordinate the activities of many cells together. Chapter 8 describes the anatomy and physiology of animals, focusing on the cardiovascular, immune, and nervous systems. Chapter 9 describes the fundamentals of human disease and its treatment, focusing on infections, heart disease, and cancer. Chapter 10 explains contemporary biotechnology, describing the instruments that make this science possible, and the genetic engineering that is one of the foremost changes molecular biology brings to the wider world. Chapter 11 concludes the book with a brief discussion of bioethics, and a consideration of the profound questions that our growing understanding of molecular biology is raising for society.

Although I have attempted to at least briefly introduce as many central issues in molecular biology as possible, several important aspects of the field were largely left out. Perhaps the most important omission is the failure to describe the experimental methodologies that generated the knowledge described here. Although chapter 10 does touch on some of the instruments used by biologists, the extraordinary diversity of clever experimental approaches is simply too overwhelming to even survey. Learning how to conceive of and evaluate experimental methodology is one of the subtlest parts of molecular biology; absorbing the material here is a necessary prerequisite for those interested in that work.

The other important omission is the downplaying of ecological approaches to understanding life. Living things all exist in the midst of complex communities of other organisms, called **ecosystems**. While brief discussions of the many consequences of living in an ecosystem are scattered throughout the text, many issues that relate to ecosystems as a whole, such as biodiversity, ecosystem services (such as nutrient cycles), and ecosystem dynamics (how ecosystems respond to perturbations) are not discussed, primarily because the molecular basis of these important topics remains largely unknown.

This is an exciting time to be learning about molecular biology. While this book is dense with new ideas and new terms, no background beyond a secondary school education is assumed. With this volume, dedication alone (and frequent references to the glossary) ought to be enough to get a solid grounding in all of the basic material you need to open the door to the exciting world of molecular biomedicine.