

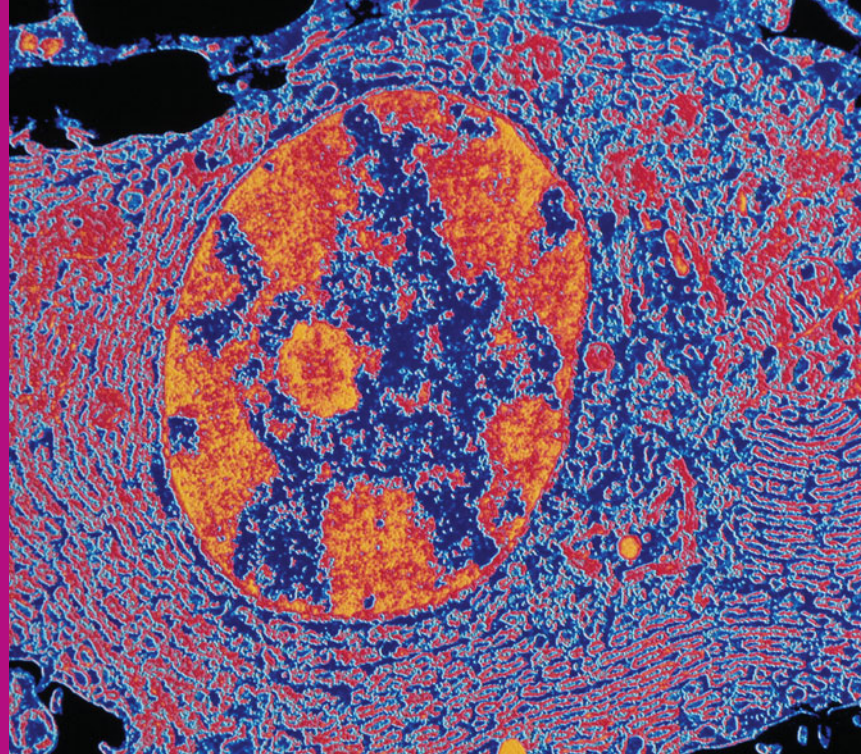
A detailed electron micrograph of a cell. The image shows a large, roughly spherical nucleus in the upper right quadrant, containing a dense network of chromatin and a prominent nucleolus. Surrounding the nucleus are numerous mitochondria, characterized by their double-membrane structure and internal folds called cristae. The cytoplasm is filled with various organelles and a complex network of membranes. The overall color palette is dominated by shades of green, blue, and orange, representing different cellular components.

3

Cells

The smallest part
of you

1 What is a cell?



Human cell, packed with organelles.

3.1

All organisms are made of cells.

Where do we begin if we want to understand how organisms work? Given their complexity, this task can be daunting. Fortunately, as with most complex things, a strategy of divide and conquer comes in handy. In the case of organisms, whether we are studying a creature as small as a flea or as large as an elephant or giant sequoia, they can be broken down into smaller units that are more easily studied and understood (FIGURE 3-1). The most basic unit of any organism is the **cell**, the smallest unit of life that can function independently and perform all the necessary functions of life, including reproducing itself. Understanding cell structure and function is the basis for our understanding of how complex organisms are organized.

The term “cell” was first used in the mid-1600s by Robert Hooke, a British scientist also known for his contributions to philosophy, physics, and architecture. When he was made Curator of Experiments for the Royal Society of London, Hooke suddenly had access to many of the first microscopes available, and he began to examine everything he could get his hands on. Because Hooke thought the close-up views of a very thin piece of cork resembled a mass of small, empty rooms, he named these compartments *cellulae*, Latin for “small rooms.”

Today, we know that a cell is a three-dimensional structure, like a fluid-filled balloon, in which many of the essential chemical reactions of life take place (such as the breakdown of carbohydrates for energy, the modification of cholesterol to

create testosterone and estrogen, and the translation of the genetic code into protein production). Generally, these reactions involve transporting raw materials and fuel into the cell and exporting finished materials and waste products out of the cell. In addition, nearly all cells contain DNA (deoxyribonucleic acid), a molecule that contains the information that directs the chemical reactions in a cell, the formation of various cellular products within the cell, and the cell’s ability to reproduce itself. (A few types of cells, including mammalian red blood cells and cells called “sieve tube elements” that form part of the plant circulatory system, lose their nuclei after they are created and are unable to divide.) We explore all of these features of cell functioning in this and the next three chapters.

To see a cell, you don’t have to work in a lab or use a microscope. Just open your refrigerator. Chances are you’ve got a dozen or so visible cells in there: eggs. Although most cells are too small to see with the naked eye, there are a few exceptions, including hens’ eggs from the supermarket, each of which is an individual cell. The ostrich egg, weighing about three pounds, is the largest of all cells. In addition to being among the largest cells around, eggs are also the most valuable. Almas caviar, eggs from the beluga sturgeon, sells for nearly \$700 per ounce. This value is exceeded only by that of human eggs, which currently fetch as much as \$25,000 for a dozen or so eggs on the open market (FIGURE 3-2). (Human sperm cells command only about a penny per 20,000 cells!)



FIGURE 3-1 What do these diverse organisms have in common? Cells.

Most cells are much smaller than hens' eggs and ostrich eggs. Consider that, at this very moment, there are probably more than seven billion bacteria in your mouth—even if you just brushed your teeth! This is more than the number of people on earth. It is possible to squeeze so many bacteria in there because most cells (not just bacteria) are really, really tiny—so tiny that 2,000 red blood cells, lined up end to end, would just extend across a dime.

After sufficient improvements were made to early microscopes in the 19th century, the central role of the cell in biology could be understood. As scientists began putting everything they studied under their microscopes, the importance and universality of the cell finally dawned on them. By the 1830s, scientists realized that all plants and animals were made entirely from cells. Subsequent studies revealed that every cell seemed to arise from the division of another cell. You, for example, are made up of at least 60 trillion cells, all of which came from just one cell: the single fertilized egg produced when an egg cell from your mother was fertilized by a sperm cell from your father.

The facts that (1) all living organisms are made up of one or more cells and (2) all cells arise from other, pre-existing cells are the foundations of **cell theory**, one of the unifying theories in biology, and one that is universally accepted by all biologists. As

we will see in Chapter 10, the origin of life on earth was a one-time deviation from cell theory: the first cells on earth probably originated from free-floating molecules in the oceans early in the earth's history (about 3.5 billion years ago). Since that time, however, all cells and thus all life have been produced as a continuous line of cells, originating from these initial cells.

In this chapter, we investigate the two different kinds of cells that make up all of the organisms on earth, the processes by which cells control how materials move into and out of the cell, and how cells communicate with each other. We also explore some of the important landmarks found in many cells. We look, too, at the specialized roles these structures play in a variety of cellular functions and learn about some of the health consequences that occur when they malfunction.

TAKE-HOME MESSAGE 3.1

The most basic unit of any organism is the cell, the smallest unit of life that can function independently and perform all of the necessary functions of life, including reproducing itself. All living organisms are made up of one or more cells, and all cells arise from other, pre-existing cells.



Hummingbird egg: 0.02 ounce
Elephant bird (extinct) egg: two gallons

Beluga sturgeon eggs: \$700 per ounce

Human eggs: Thousands of dollars per egg



Eggs are the largest and most expensive cells in the world!

FIGURE 3-2 Not all cells are tiny. And some cells are extremely valuable!

Prokaryotic cells are structurally simple, but there are many types of them.

Although there are millions of diverse species on earth, billions of unique organisms alive at any time, and trillions of different cells in many of those organisms, every cell on earth falls into one of two basic categories.

A **eukaryotic cell** (from the Greek for “good” and “kernel”) has a central control structure called a nucleus, which contains the cell’s DNA. Organisms composed of eukaryotic cells are called **eukaryotes**.

A **prokaryotic cell** (from the Greek for “before” and “kernel”) does not have a nucleus; its DNA simply resides in the middle of the cell. An organism consisting of a prokaryotic cell is called a **prokaryote**.

We begin our study of the cell by exploring the prokaryotes. Prokaryotes were the first cells on earth, making their appearance about 3.5 billion years ago, and, for a long time (1.5 billion years), they had the planet to themselves.

All prokaryotes are one-celled organisms and are thus invisible to the naked eye. Prokaryotes have four basic structural features (**FIGURE 3-3**).

1. A **plasma membrane** encompasses the cell (and is sometimes simply called the “cell membrane”). For this reason, anything inside the plasma membrane is referred to as “intracellular,” and everything outside the plasma membrane is “extracellular.”
2. The **cytoplasm** is the jelly-like fluid that fills the inside of the cell.
3. **Ribosomes** are little granular bodies where proteins are made; thousands of them are scattered throughout the cytoplasm.
4. Each prokaryote has one or more circular loops or linear strands of DNA.

In addition to the characteristics common to all prokaryotes, some prokaryotes have additional, unique features. Many have a rigid **cell wall**, for example, that protects and gives shape to the cell. Some have a slimy, sugary capsule as their outermost layer. This sticky outer coat provides protection and enhances the prokaryotes’ ability to anchor themselves in place when necessary.

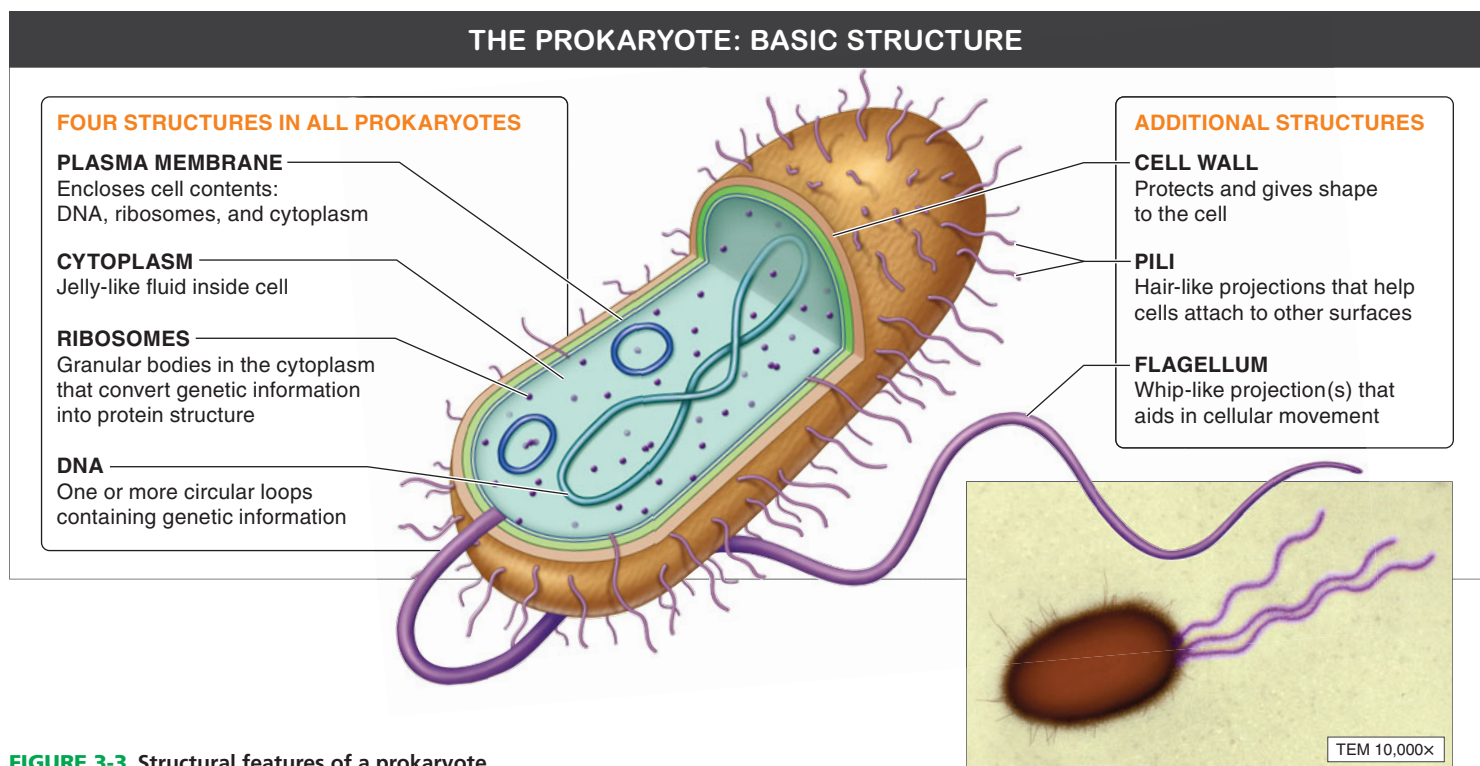


FIGURE 3-3 Structural features of a prokaryote.

Many prokaryotes have a **flagellum** (*pl. flagella*), a long, thin, whip-like projection that rotates like a propeller and moves the cell through the medium in which it lives. Other appendages include **pili** (*sing. pilus*), much thinner, hair-like projections that help prokaryotes attach to surfaces.

From our human perspective, it is easy to underestimate the prokaryotes. Although they are smaller, evolutionarily older, and structurally more simple than eukaryotes, prokaryotes are fantastically diverse metabolically (i.e., in the way they break down and build up molecules). Among many other innovations, bacteria can fuel their activities in the presence or absence of oxygen, using almost any energy source on earth, depending on the type of bacteria—from the sulfur in deep-sea hydrothermal vents to hydrogen to the sun.

You may think you've never encountered a prokaryote, but you are already familiar with the largest group of prokaryotes: the bacteria. All bacteria are prokaryotes, from those such as *Escherichia coli* (*E. coli*), which live in your intestine and help your body make some essential vitamins, to those responsible for illness, such as *Streptococcus pyogenes*, which causes strep throat. Another recently discovered group of organisms, the archaea, are also prokaryotes.

TAKE-HOME MESSAGE 3•2

Every cell on earth is either a eukaryotic or a prokaryotic cell. Prokaryotes, which have no nucleus, were the first cells on earth. They are all single-celled organisms. Prokaryotes include the bacteria and archaea and, as a group, are characterized by tremendous metabolic diversity.

3•3

Eukaryotic cells have compartments with specialized functions.

Eukaryotes showed up about 1.5 billion years after prokaryotes, and in the 2 billion years that they have been on earth, they have evolved into some of the most dramatic and interesting creatures, such as platypuses, dolphins, giant

sequoias, and the Venus fly trap. Because all prokaryotes are single-celled and thus invisible to the naked eye, every organism that we see around us is a eukaryotic organism. (FIGURE 3-4). All fungi, plants, and animals are eukaryotes, for

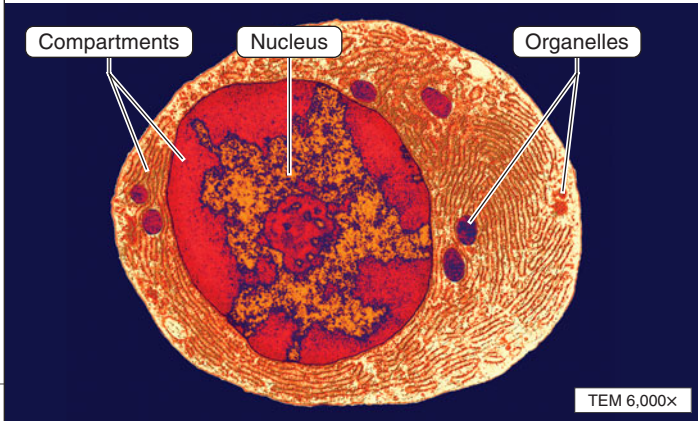


FIGURE 3-4 Diversity of the eukaryotes. Every organism that we can see without magnification is a eukaryotic organism.

EUKARYOTES vs. PROKARYOTES

TYPICAL EUKARYOTIC CELL FEATURES

- DNA contained in nucleus
- Internal structures organized into compartments
- Larger than prokaryotes—usually 10 times bigger
- Cytoplasm contains specialized structures called organelles



TYPICAL PROKARYOTIC CELL FEATURES

- No nucleus—DNA is in the cytoplasm
- Internal structures not organized into compartments
- Much smaller than eukaryotes

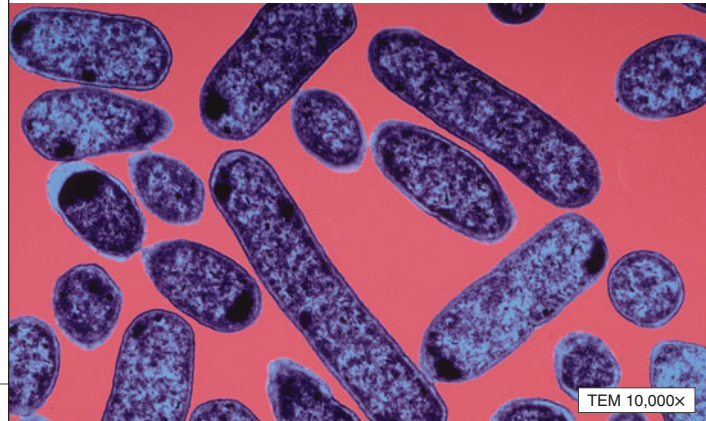


FIGURE 3-5 Comparison of eukaryotic and prokaryotic cells.

instance. Not all eukaryotes are multicellular, however. There is a huge group of eukaryotes, called the Protista (or protists), nearly all of which are single-celled organisms visible only with a microscope.

The chief distinguishing feature of eukaryotic cells is the presence of a **nucleus**, a membrane-enclosed structure that contains linear strands of DNA. In addition to a nucleus, eukaryotic cells usually contain in their cytoplasm several other specialized structures, called **organelles**, many of which are enclosed separately within their own lipid membranes. Eukaryotic cells are also about 10 times larger than prokaryotes. All of these physical differences make it easy to distinguish eukaryotes from prokaryotes under a microscope (**FIGURE 3-5**).

Organelles enable eukaryotic cells to do many things that a prokaryotic cell cannot do. Most important, the creation of physically separate compartments means that there can be distinct areas within the same cell in which different chemical reactions can occur simultaneously. In the non-compartmentalized interior of a prokaryotic cell, random molecular movements quickly blend the chemicals throughout the cell, reducing the ease with which different reactions can occur simultaneously.

FIGURE 3-6 illustrates a generalized animal cell and a generalized plant cell. Because they share a common,

eukaryotic ancestor, they have much in common. Both can have a plasma membrane, nucleus, cytoskeleton, and ribosomes, and a host of organelles, including rough and smooth endoplasmic membranes, Golgi apparatus, and mitochondria. Animal cells have centrioles, which are not present in most plant cells. Plant cells have a rigid cell wall (as do fungi and many protists) and chloroplasts (also found in some protists). Plants also have a vacuole, a large central chamber (only occasionally found in animal cells). We explore each of these plant and animal organelles in detail later in this chapter.

When you compare a complex eukaryotic cell with the structurally simple prokaryotic cell, it's hard not to wonder how eukaryotic cells came about. How did they get filled up with so many organelles? We can't go back 2 billion years to watch the initial evolution of eukaryotic cells, but we can speculate about how it might have occurred. One very appealing idea, called the **endosymbiosis theory**, has been developed to explain the presence of two organelles in eukaryotes: chloroplasts in plants and algae, and mitochondria in plants and animals. Chloroplasts help plants and algae convert sunlight into a more usable form of energy. Mitochondria help plants and animals harness the energy stored in food molecules. (Chapter 4, on energy, explains the details of both of these processes.)

According to the theory of endosymbiosis, two different types of prokaryotes may have set up close partnerships with each

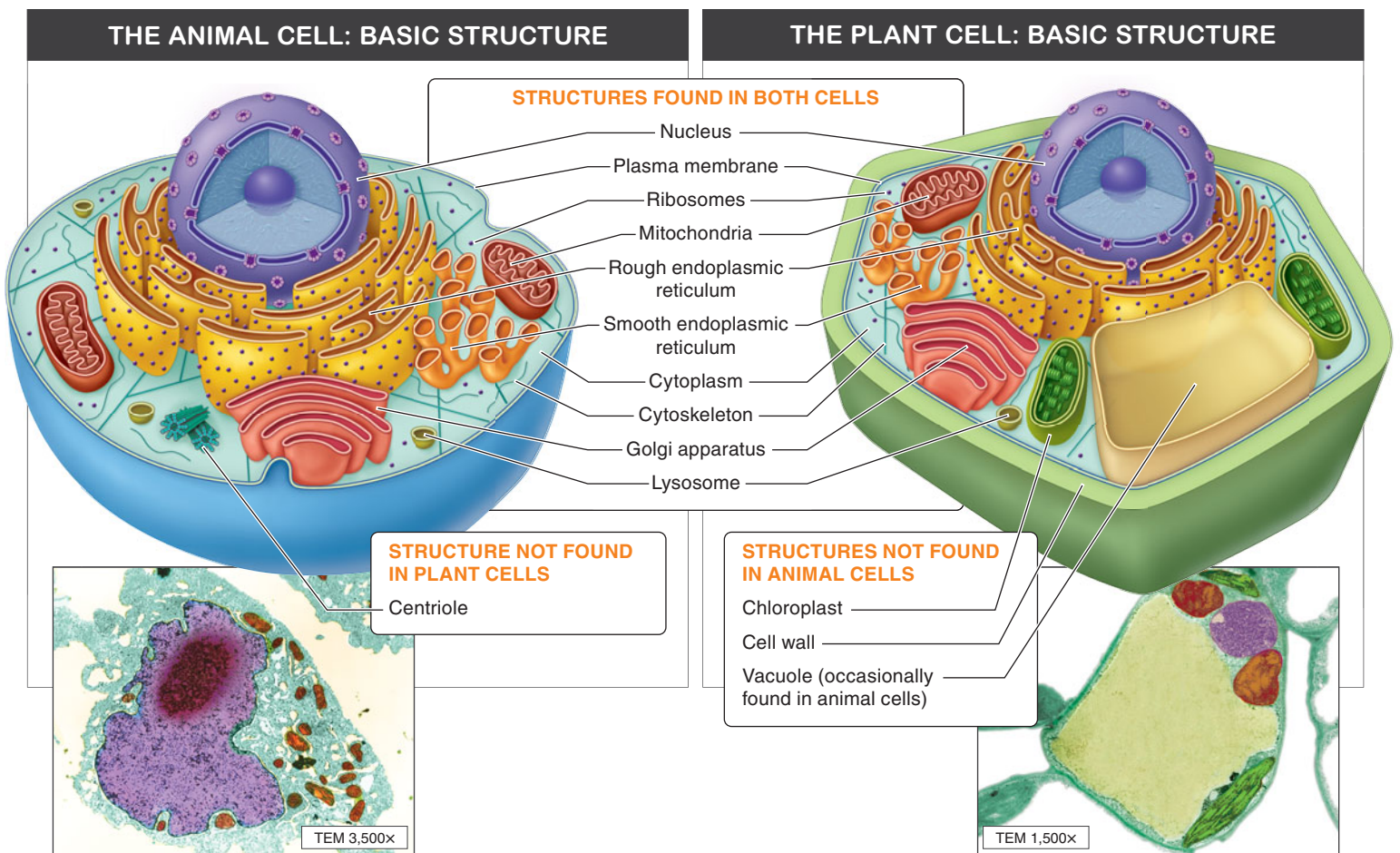


FIGURE 3-6 Structures found in animal and plant cells.

other. For example, some small prokaryotes capable of performing photosynthesis (the process by which plant cells capture light energy from the sun and transform it into the chemical energy stored in food molecules) may have come to live inside a larger “host” prokaryote. The photosynthetic “boarder” may have made some of the energy from its photosynthesis available to the host.

After a long while, the two cells may have become more and more dependent on each other until neither cell could live without the other (they became “symbiotic”), and they became a single, more complex organism. Eventually, the photosynthetic prokaryote evolved into a **chloroplast**, the organelle in plant cells in which photosynthesis occurs. A similar scenario might explain how a prokaryote unusually efficient at converting food and oxygen into easily usable energy took up residence inside another, host prokaryote and evolved into a **mitochondrion**, the organelle in plant and

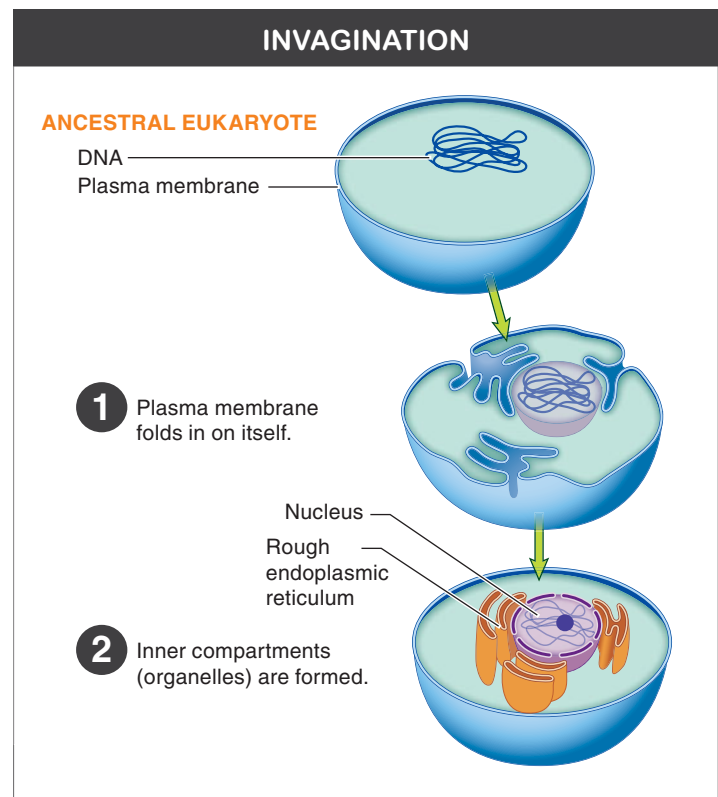
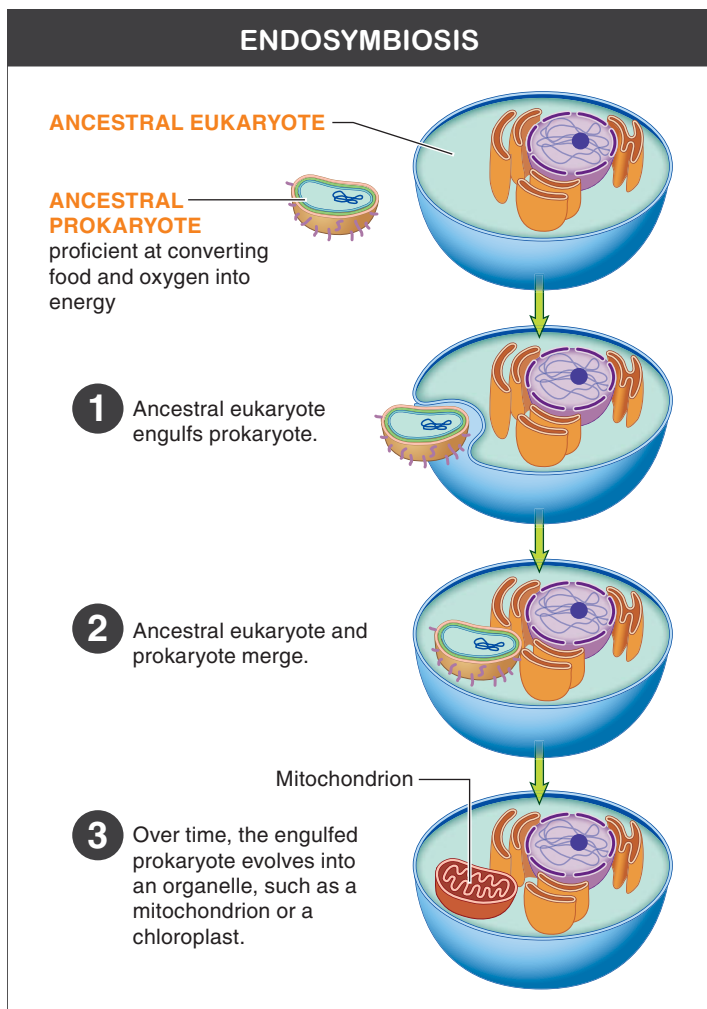
Q Humans, deep down, may be part bacteria. How can that be?

animal cells that converts the energy stored in food into a form usable by the cell (**FIGURE 3-7**).

The idea of endosymbiosis is supported by several observations.

1. Chloroplasts and mitochondria are similar in size to prokaryotic cells.
2. Chloroplasts and mitochondria have small amounts of circular DNA, similar to the circular DNA in prokaryotes and in contrast to the linear DNA strands found in a eukaryote’s nucleus.
3. Chloroplasts and mitochondria divide by splitting (fission), just like prokaryotes.
4. Chloroplasts and mitochondria have internal structures called ribosomes that are similar to those found in bacteria.

In addition to the theory of endosymbiosis as an explanation for the existence of chloroplasts and mitochondria, another



Organelles may have developed by endosymbiosis or invagination or a combination of the two.

FIGURE 3-7 How did eukaryotic cells become so structurally complex? Two theories.

theory about the origin of organelles in eukaryotes is the idea that the plasma membrane around the cell may have folded in on itself (a process called **invagination**) to create the inner compartments, which subsequently became modified and specialized (see Figure 3-7). It may turn out that organelles arose from both processes. Perhaps mitochondria and chloroplasts originated from endosymbiosis, and all of the other organelles arose from plasma membrane invagination. We just don't know.

TAKE-HOME MESSAGE 3.3

Eukaryotes are single-celled or multicellular organisms consisting of cells with a nucleus that contains linear strands of genetic material. The cells also commonly have organelles throughout their cytoplasm; these organelles may have originated evolutionarily through endosymbiosis or invagination, or both.