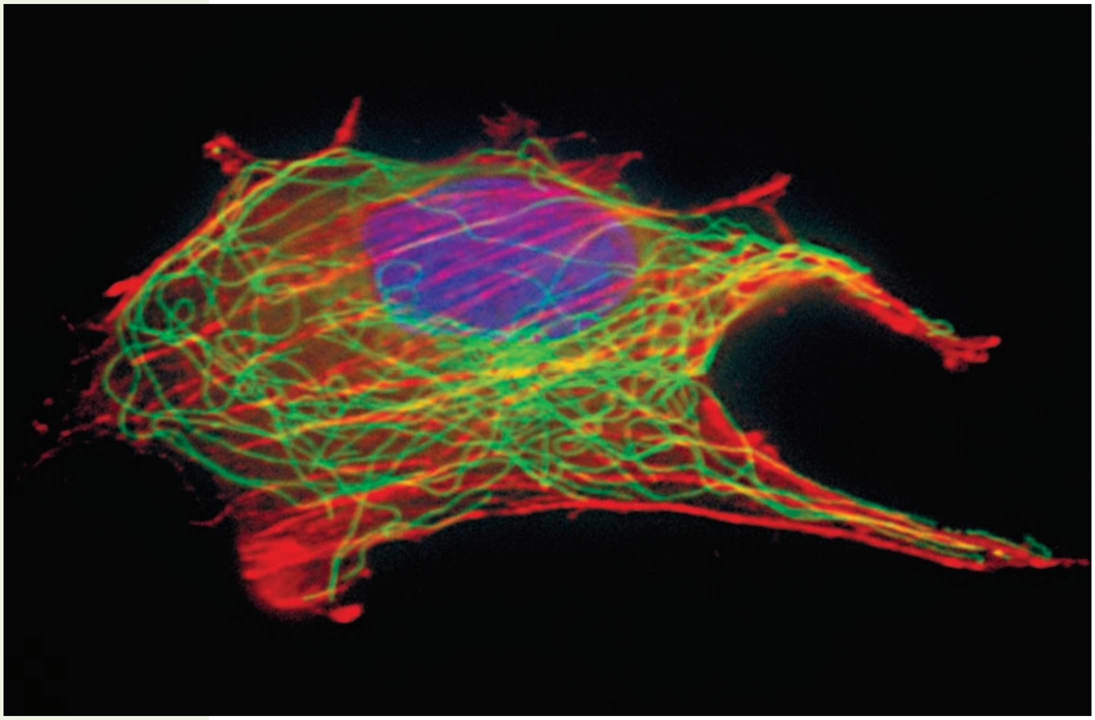
4

Organization of the Cell



Jennifer C. Waters/Photo Researchers, Inc.

The cytoskeleton. The cell shown here was stained with fluorescent antibodies (specific proteins) that bind to proteins associated with DNA (*purple*) and to a protein (tubulin) in microtubules (*green*). Microfilaments (*red*) are also visible. This type of microscopy, known as confocal fluorescence microscopy, shows the extensive distribution of microtubules in this cell.

KEY CONCEPTS

4.1 The cell is the basic unit of life; its organization and size are critical in maintaining homeostasis, and its size and shape are adapted for its function.

4.2 Biologists study cells using microscopes and biochemical techniques such as cell fractionation.

4.3 Unlike prokaryotic cells, eukaryotic cells have internal membranes that divide the cell into compartments, allowing cells to conduct specialized activities within separate, small areas.

4.4 In eukaryotic cells, genetic information coded in DNA is located in the nucleus, which is typically the most prominent organelle in the cell.

4.5 Among the many organelles in the cytoplasm are ribosomes, which synthesize proteins; endoplasmic reticulum and Golgi complexes, which process proteins; and mitochondria and chloroplasts, which convert energy from one form to another.

4.6 The cytoskeleton is a dynamic internal framework that functions in various types of cell movement.

4.7 Most eukaryotic cells are surrounded by a cell coat; in addition, many animal cells are surrounded by an extracellular matrix; cells of most bacteria, archaea, fungi, and plants are surrounded by a cell wall.

The cell is the smallest unit that can carry out all activities we associate with life. When provided with essential nutrients and an appropriate environment, some cells can be kept alive and growing in the laboratory for many years. By contrast, no isolated part of a cell is capable of sustained survival. As you read this chapter, recall the discussion of systems biology in Chapter 1. Even as we describe individual components of cells, we discuss how these components work together, generating complex biological systems within the cell. The cell itself is a highly intricate biological system, and groups of cells make up tissues, organs, and organisms. Each of these is a biological system.

Most prokaryotes and many protists and fungi consist of a single cell. In contrast, most plants and animals are composed of millions of cells. Cells are the building blocks of complex multicellular organisms. Although they are basically similar, cells are also extraordinarily diverse and versatile. They are modified in a variety of ways to carry out specialized functions.

The cell is composed of a vast array of inorganic and organic ions and molecules, including water, salts, carbohydrates, lipids, proteins, and nucleic acids. These molecules are organized to form the structures within the cell and its biochemical pathways. Genetic information is stored in DNA molecules and is faithfully replicated. This information is passed to each new generation of cells during cell division. Information in DNA codes for specific proteins that, in turn, determine cell structure and function.

Cells exchange materials and energy with the environment. All living cells need one or more sources of energy, but a cell rarely obtains energy in a form that is immediately usable. Cells convert energy from one form to another, and that energy is used to carry out various activities, ranging from mechanical work to chemical synthesis. Cells convert energy to a convenient form, usually chemical energy stored in adenosine triphosphate, or ATP (see Chapter 3).

Both the chemical reactions that convert energy from one form to another and the mechanisms of information transfer are essentially the same in all cells, from those in bacteria to those of large, multicellular plants and animals. Such similarities suggest evolutionary relationships.

Thanks to advances in technology, cell biologists use increasingly sophisticated tools in their search to better understand the structure and function of cells. For example, investigation of the cytoskeleton (cell skeleton), currently an active and exciting area of research, has been greatly enhanced by advances in microscopy. In the photomicrograph, we see the extensive distribution of microtubules in cells. Microtubules are key components of the cytoskeleton. They help maintain cell shape, function in cell movement, and facilitate transport of materials within the cell.

4.1 THE CELL: BASIC UNIT OF LIFE

LEARNING OBJECTIVES

1. Describe the cell theory and relate it to the evolution of life.
2. Summarize the relationship between cell organization and homeostasis.
3. Explain the relationship between cell size and homeostasis.

Cells, the building blocks of organisms, are dramatic examples of the underlying unity of all living things.

The cell theory is a unifying concept in biology

Two German scientists, botanist Matthias Schleiden in 1838 and zoologist Theodor Schwann in 1839, used inductive reasoning to conclude that all plants and animals consist of cells. These investigators used their own observations and those of other scientists to reach their conclusions. Later, Rudolf Virchow, another German scientist, observed cells dividing and giving rise to daughter cells. In 1855, Virchow proposed that new cells form only by the division of previously existing cells. The work of Schleiden, Schwann, and Virchow contributed greatly to the development of the **cell theory,** the unifying concept that (1) cells are the basic living units of organization and function in all organisms and (2) that all cells come from other cells.

About 1880, another German biologist, August Weismann, added an important corollary to Virchow's concept by pointing out that the ancestry of all the cells alive today can be traced back to ancient times. Evidence that all living cells have a common origin is provided by the basic similarities in their structures and in the molecules of which they are made. When we examine a variety of diverse organisms, ranging from simple bacteria to the most complex plants and animals, we find striking similarities at the cellular level. Careful studies of shared cell characteristics help us trace the evolutionary history of various organisms and furnish powerful evidence that all organisms alive today had a common origin.

The organization of all cells is basically similar

The organization of cells and their small size allow them to maintain **homeostasis,** an appropriate internal environment. Cells experience constant changes in their environments, such as deviations in salt concentration, pH, and temperature. They must work continuously to restore and maintain the internal conditions that enable their biochemical mechanisms to function.

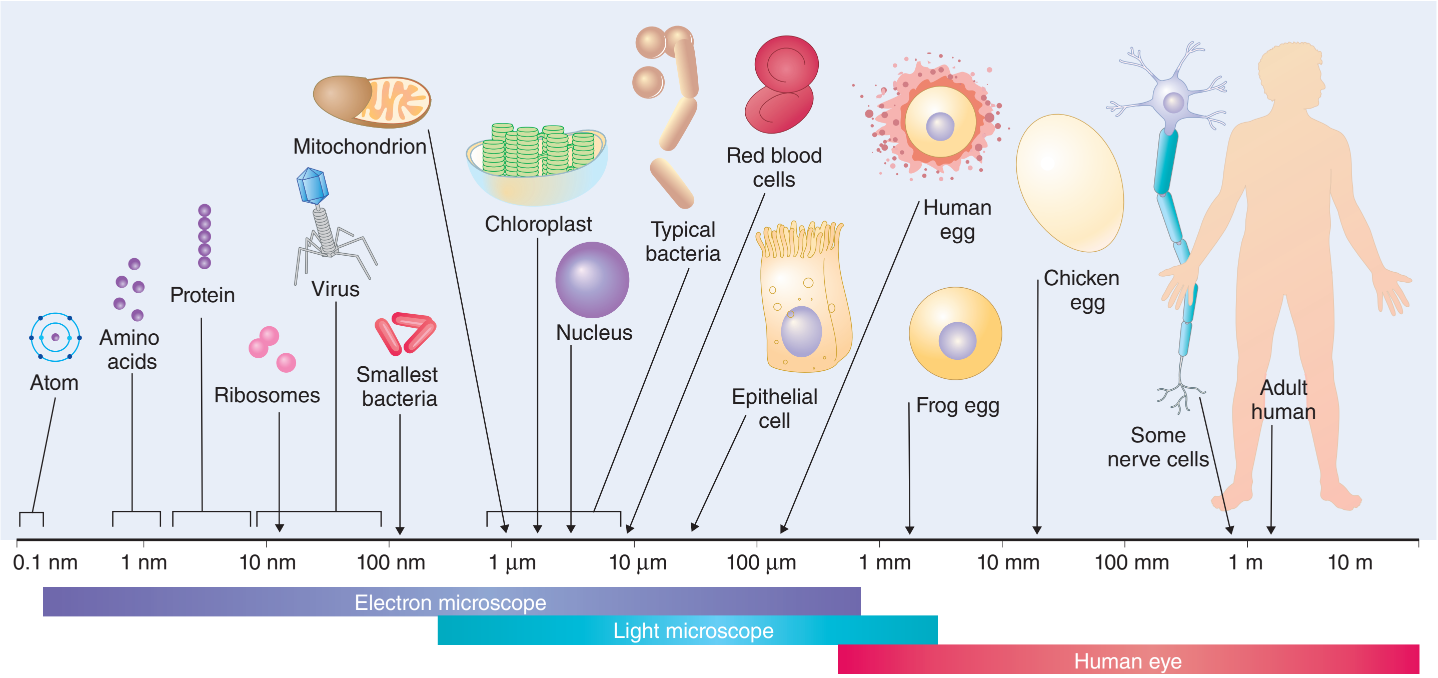
In order for the cell to maintain homeostasis, its contents must be separated from the external environment. The **plasma membrane** is a structurally distinctive surface membrane that surrounds all cells. By making the interior of the cell an enclosed compartment, the plasma membrane allows the chemical composition of the cell to be different from that outside the cell. The plasma membrane serves as a selective barrier between the cell contents and the outer environment. Cells exchange materials with the environment and can accumulate needed substances and energy stores.

Most cells have internal structures, called **organelles,** that are specialized to carry out metabolic activities, such as converting energy to usable forms, synthesizing needed compounds, and manufacturing structures necessary for functioning and reproduction. Each cell has genetic instructions coded in its DNA, which is concentrated in a limited region of the cell.

Cell size is limited

Although their sizes vary over a wide range (**FIG. 4-1**), most cells are microscopic and must be measured by very small units. The basic unit of linear measurement in the metric system (see inside back cover) is the meter (m), which is just a little longer than a yard. A millimeter (mm) is 1/1000 of a meter and is about as long as the bar enclosed in parentheses (-). The micrometer (μm) is the most convenient unit for measuring cells. A bar 1 μm long is 1/1,000,000 (one millionth) of a meter, or 1/1000 of a millimeter—far too short to be seen with the unaided eye. Most of us have difficulty thinking about units that are too small to see, but it is helpful to remember that a micrometer has the same relationship to a millimeter that a millimeter has to a meter (1/1000).

As small as it is, the micrometer is actually too large to measure most cell components. For this purpose biologists use the nanometer (nm), which is 1/1,000,000,000 (one billionth) of a meter, or 1/1000 of a micrometer. To mentally move down to the world of the nanometer, recall that a millimeter is 1/1000 of a meter, a micrometer is 1/1000 of a millimeter, and a nanometer is 1/1000 of a micrometer.



Measurements		
1 meter	=	1000 millimeters (mm)
1 millimeter	=	1000 micrometers (µm)
1 micrometer	=	1000 nanometers (nm)

FIGURE 4-1 **Biological size and cell diversity**

We can compare relative size from the chemical level to the level of an entire organism by using a logarithmic scale (multiples of 10). The prokaryotic cells of most bacteria range in size from 1 to 10 μm long. Most eukaryotic cells are between 10 and 30 μm in diameter. Mitochondria are about the size of small bacteria, whereas chloroplasts are usually larger, about 5 μm long. Ova (egg cells) are among the largest cells. Although microscopic, some nerve cells are very long. The cells shown here are not drawn to scale.

A few specialized algae and animal cells are large enough to be seen with the naked eye. A human egg cell, for example, is about 130 μm in diameter, or approximately the size of the period at the end of this sentence. The largest cells are birds' eggs, but they are not typical cells because they include large amounts of food reserves—the yolk and the egg white. The functioning part of the cell is a small mass on the surface of the yolk.

Why are most cells so small? If you consider what a cell must do to maintain homeostasis and to grow, it may be easier to understand the reasons for its small size. A cell must take in food and other materials and must rid itself of waste products generated by metabolic reactions. Everything that enters or leaves a cell must pass through its plasma membrane. The plasma membrane contains specialized "pumps" and channels with "gates" that selectively regulate the passage of materials into and out of the cell. The plasma membrane must be large enough relative to the cell volume to keep up with the demands of regulating the passage of materials. Thus, a critical factor in determining cell size is the ratio of its surface area (the plasma membrane) to its volume (**FIG. 4-2**).

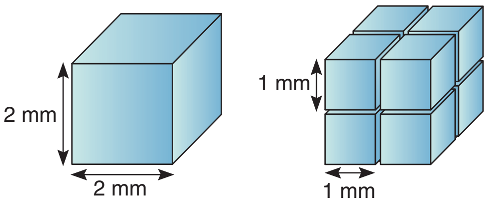
As a cell becomes larger, its volume increases at a greater rate than its surface area (its plasma membrane), which effectively places an upper limit on cell size. Above some critical size, the number of molecules required by the cell could not be transported into the cell fast enough to sustain its needs. In addition, the cell would not be able to regulate its concentration of various ions or efficiently export its wastes.

Of course, not all cells are spherical or cuboid. Because of their shapes, some very large cells have relatively favorable ratios of surface area to volume. In fact, some variations in cell shape represent a strategy for increasing the ratio of surface area to volume. For example, many large plant cells are long and thin, which increases their surface area–to-volume ratio. Some cells, such as epithelial cells lining the small intestine, have fingerlike projections of the plasma membrane, called **microvilli,** that significantly increase the surface area for absorbing nutrients and other materials (see Fig. 47-10).

Another reason for the small size of cells is that, once inside, molecules must be transported to the locations where they are converted into other forms. Because cells are small, the distances molecules travel within them are relatively short. Thus, molecules are rapidly available for cell activities.

Cell size and shape are adapted to function

The sizes and shapes of cells are adapted to the particular functions they perform. Some cells, such as amoebas and white blood



Surface Area (mm^2)	Surface area = height × width × number of sides × number of cubes	24 (2 × 2 × 6 × 1)	48 (1 × 1 × 6 × 8)
Volume (mm^3)	Volume = height × width × length × number of cubes	8 (2 × 2 × 2 × 1)	8 (1 × 1 × 1 × 8)
Surface Area/ Volume Ratio	Surface area/ volume	3 (24:8)	6 (48:8)

FIGURE 4-2 **Surface area–to-volume ratio**

The surface area of a cell must be large enough relative to its volume to allow adequate exchange of materials with the environment. Although their volumes are the same, eight small cells have a much greater surface area (plasma membrane) in relation to their total volume than one large cell does. In the example shown, the ratio of the total surface area to total volume of eight 1 mm cubes is double the surface area–to-volume ratio of the single large cube.

cells, change their shape as they move about. Sperm cells have long, whiplike tails, called *flagella,* for locomotion. Nerve cells have long, thin extensions that enable them to transmit messages over great distances. The extensions of some nerve cells in the human body may be as long as 1 meter! Certain epithelial cells are almost rectangular and are stacked much like building blocks to form sheetlike tissues. (Epithelial tissue covers the body and lines body cavities.)

Review

- How does the cell theory contribute to our understanding of the evolution of life?
- How does the plasma membrane help maintain homeostasis?
- Why is the relationship between surface area and volume of a cell important in detemining cell-size limits?

4.2 METHODS FOR STUDYING CELLS

LEARNING OBJECTIVE

4 Describe methods that biologists use to study cells, including microscopy and cell fractionation.

One of the most important tools biologists use for studying cell structures is the microscope. Using a microscope he had made, Robert Hooke, an English scientist, first described cells in 1665 in his book *Micrographia.* Hooke examined a piece of cork and drew and described what he saw. Hooke chose the term *cell* because the tissue reminded him of the small rooms monks lived in. Interestingly, what Hooke saw were not actually living cells but the walls of dead cork cells (**FIG. 4-3a**). Much later, scientists recognized that the interior enclosed by the walls is the important part of living cells.

A few years after Hooke's discovery and inspired by Hooke's work, the Dutch naturalist Antonie van Leeuwenhoek viewed living cells with small lenses that he made. Leeuwenhoek was highly skilled at grinding lenses and was able to magnify images more than 200 times. Among his important discoveries were bacteria, protists, blood cells, and sperm cells. Leeuwenhoek was among the first scientists to report cells in animals. Leeuwenhoek was a merchant and not formally trained as a scientist. However, his skill, curiosity, and diligence in sharing his discoveries with scientists at the Royal Society of London brought an awareness of microscopic life to the scientific world. Unfortunately, Leeuwenhoek did not share his techniques, and it was more than 100 years later, in the late 19th century, before microscopes were sufficiently developed for biologists to seriously focus their attention on the study of cells.

Light microscopes are used to study stained or living cells

The **light microscope (LM),** the type used by most students, consists of a tube with glass lenses at each end. Because it contains several lenses, the modern light microscope is referred to as a *compound microscope.* Visible light passes through the specimen being observed and through the lenses. Light is refracted (bent) by the lenses, magnifying the image. Images obtained with light microscopes are referred to as light micrographs, or **LMs.**

Two features of a microscope determine how clearly a small object can be viewed: magnification and resolving power. **Magnification** is the ratio of the size of the image seen with the microscope to the actual size of the object. The best light microscopes usually magnify an object no more than 2000 times. **Resolution,** or **resolving power,** is the capacity to distinguish fine detail in an image; it is defined as the minimum distance between two points at which they can both be seen separately rather than as a single, blurred point. Resolving power depends on the quality of the lenses and the wavelength of the illuminating light. As the wavelength decreases, the resolution increases.

The visible light used by light microscopes has wavelengths ranging from about 400 nm (violet) to 700 nm (red); this limits the resolution of the light microscope to details no smaller than the diameter of a small bacterial cell (about 0.2 μm). By the early 20th century, refined versions of the light microscope became available.

The interior of many cells is transparent and it is difficult to discern specific cell structures. Organic chemists have contributed greatly to light microscopy by developing biological stains that enhance contrast in the microscopic image. Staining has enabled biologists to discover the many different internal cell structures,