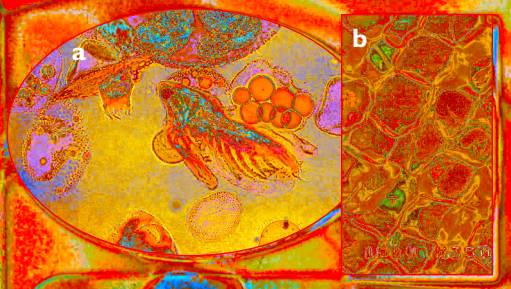
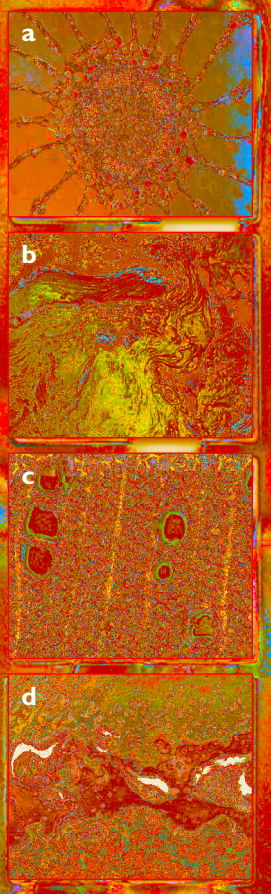
Unit C

CHAPTER 7

Cell Structure and Function



(**a**) organisms in pond water
(**b**) LM of cork



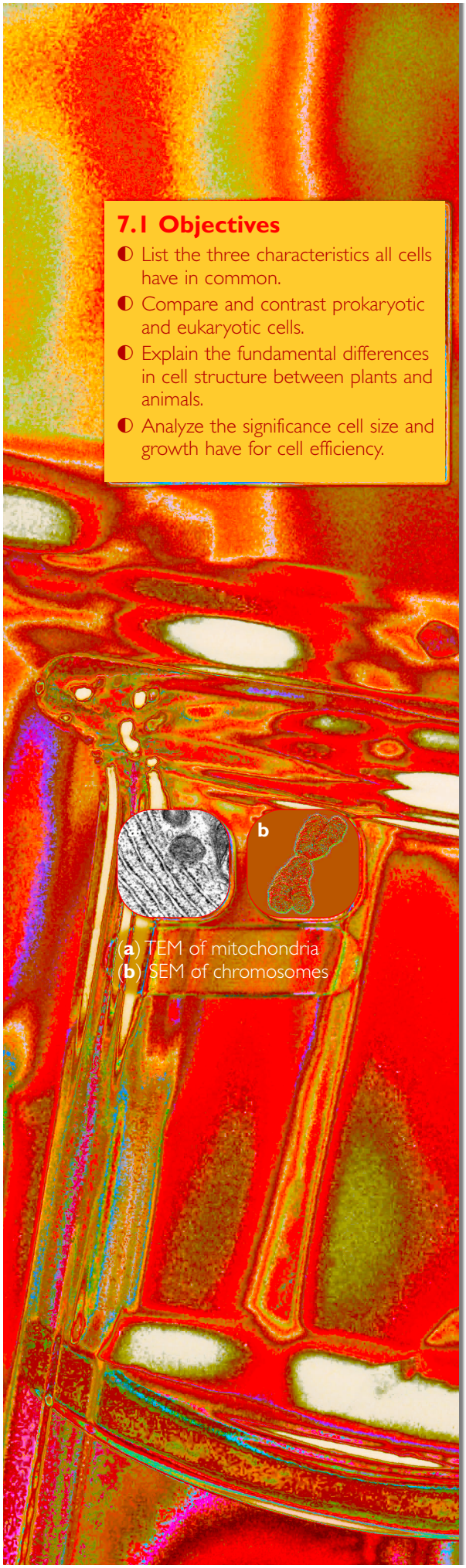
Variety of cell morphology (**a**) plant root cells (**b**) microscopic bone marrow (**c**) microscopic bone (**d**) magnification of spinal cord tissue

The discovery of cells during the seventeenth century brought about a major change in how naturalists viewed the living world. The invention of the microscope revealed not only the cellular organization of plants and animals, but also the existence of a previously unseen world within a drop of water or human blood. Advances in microscopy eventually allowed scientists to see increasingly smaller objects like bacteria and viruses.

The variety of cell shapes and sizes seems endless. Within your own body, each tissue is made up of different types of cells with different structures and shapes to enhance specific functions. Red blood cells are small, flat discs, maximizing the diffusion of oxygen across their outer membranes. Muscle cells are capable of shortening, causing the entire muscle to contract and move. Many nerve cells form branches connecting them with other nerve cells, allowing signals to be sent and received throughout the body. Yet for all their variety, your cells are distinctly animal cells, quite different from plant cells or bacteria.

As technology improved, scientists gained the ability to peer inside cells, discovering surprising complexity. It was found that most, if not all, organisms have in common many tiny structures within their cells. Consequently, while taxonomic studies revealed the incredible diversity of life, studies of cells have unified much of this apparent diversity. In spite of obvious differences between a mouse and a tomato plant, certain functions in the cells of each are not just similar but identical. As different as you are from an amoeba, many of your cell structures are the same.

Understanding an entire organism begins with understanding how its cells work. Some cellular structures and functions are so vital to life they are shared by all cells, inherited from ancestors living billions of years ago. Others are found only in particular kingdoms. Discoveries of the intricacies of cell functions have helped biologists construct cladograms because organelles and metabolic reactions are biological traits just as backbones, exoskeletons and flowers are. In this chapter we begin to explore the structure and function of cells.



7.1 Objectives

- List the three characteristics all cells have in common.
- Compare and contrast prokaryotic and eukaryotic cells.
- Explain the fundamental differences in cell structure between plants and animals.
- Analyze the significance cell size and growth have for cell efficiency.

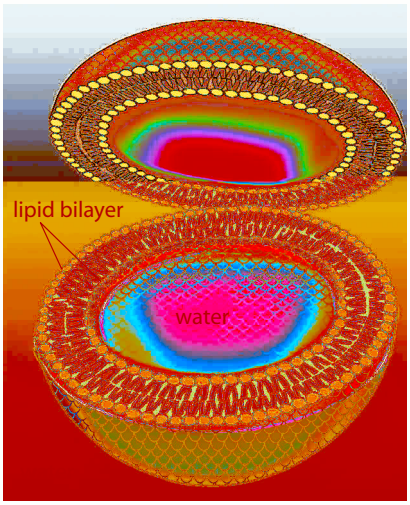
7.1 An Introduction to the Cell

Cells are the basic units of life. The beating of your heart and contraction of your diaphragm as you breathe are ultimately explained as the function of cells. The same chemical reactions providing your heart with energy also provide energy for the beating cilia of *Paramecium* or the changing pseudopodia of amoeba. Regardless of the sizes, shapes or taxonomic classifications of organisms, the processes of life are ultimately explained as the functions of cells.

Characteristics Common to All Cells

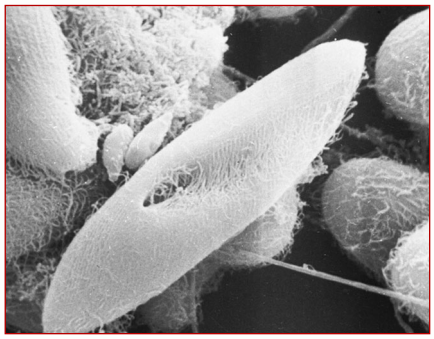
All cells have three common characteristics. First, the **plasma membrane** is the outer layer of a cell. (see Figure 7.1) It is the boundary between a cell and its environment. In some ways, the plasma membrane is a barrier, containing the cell's interior substances and keeping out unwanted materials. But the plasma membrane is also a gateway regulating what substances pass in and out of the cell. Just inside the plasma membrane is the cell's interior, or **cytoplasm**, the second common characteristic. Cytoplasm is not just a solution of nutrients, wastes and dissolved gases, but is often highly structured by internal membranes and compartments. The third and last characteristic of all cells is the **genetic material**, the DNA. In eukaryotes (protists, fungi, plants and animals) the DNA is contained within a **nucleus**, a membrane-bound region. However, in prokaryotes (bacteria) the DNA is simply concentrated in a region of the cytoplasm called the **nucleoid**. You may recall from Section 3.1, viruses are made of a DNA or RNA core surrounded by a protein coat but are not considered "alive" because they lack metabolic processes.

Figure 7.1



A phospholipid bilayer forms the outside membrane of all cells.

Figure 7.2



Eukaryotic cells are larger and more complex than prokaryotes.

When scientists began to closely study cells, they classified them into two major groups according to size and structural complexity. Prokaryotes are small simple cells, containing no nucleus or organelles. All bacteria are prokaryotes, making up the domains Archaea and Bacteria. Larger, complex cells containing a nucleus and organelles are eukaryotes. (see Figure 7.2) Organisms of the domain Eukarya are made of eukaryotic cells. In Chapter 3, you learned the four kingdoms of

Figure 7.3

A typical plant cell

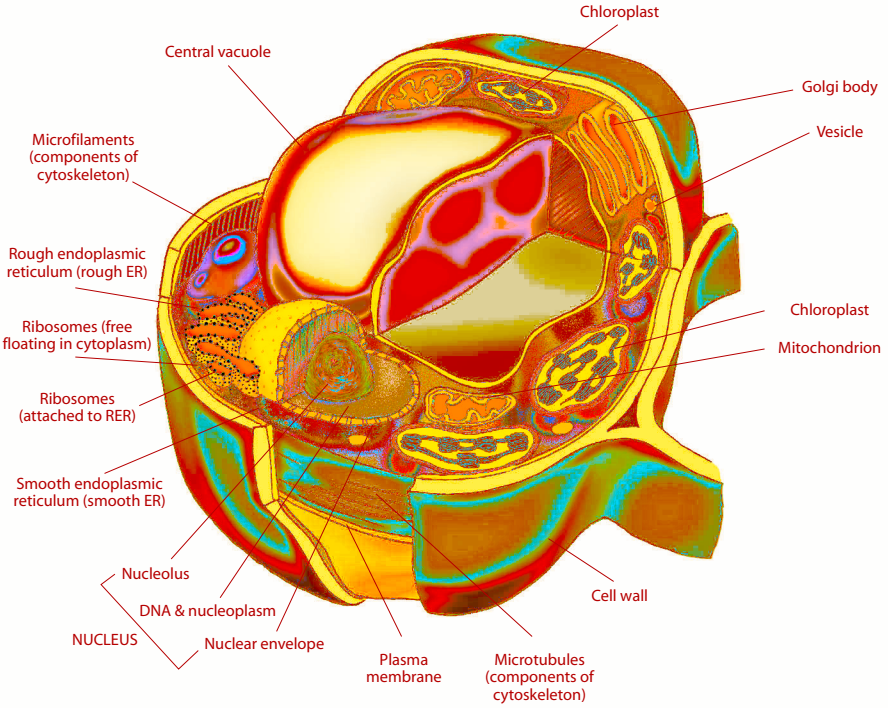


Figure 7.4

A typical animal cell

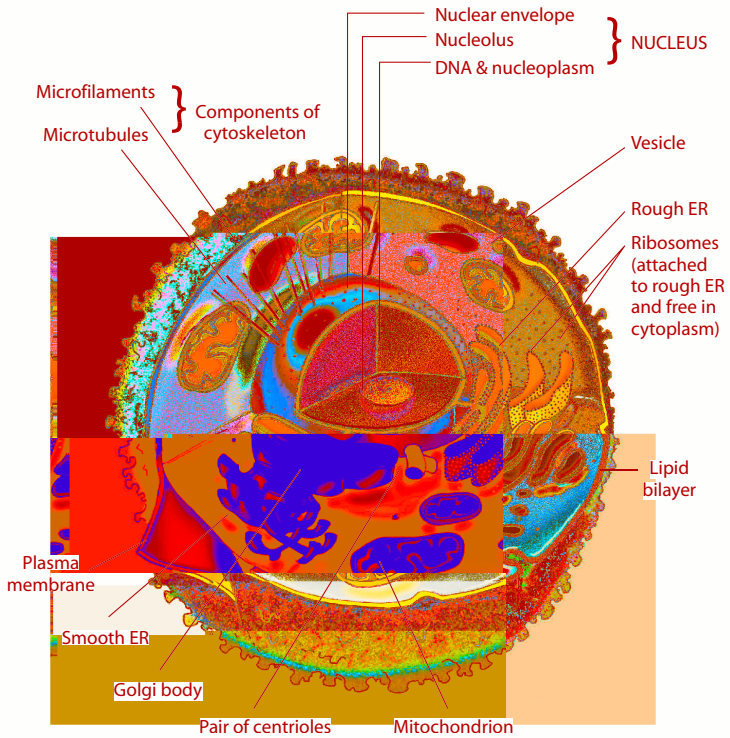
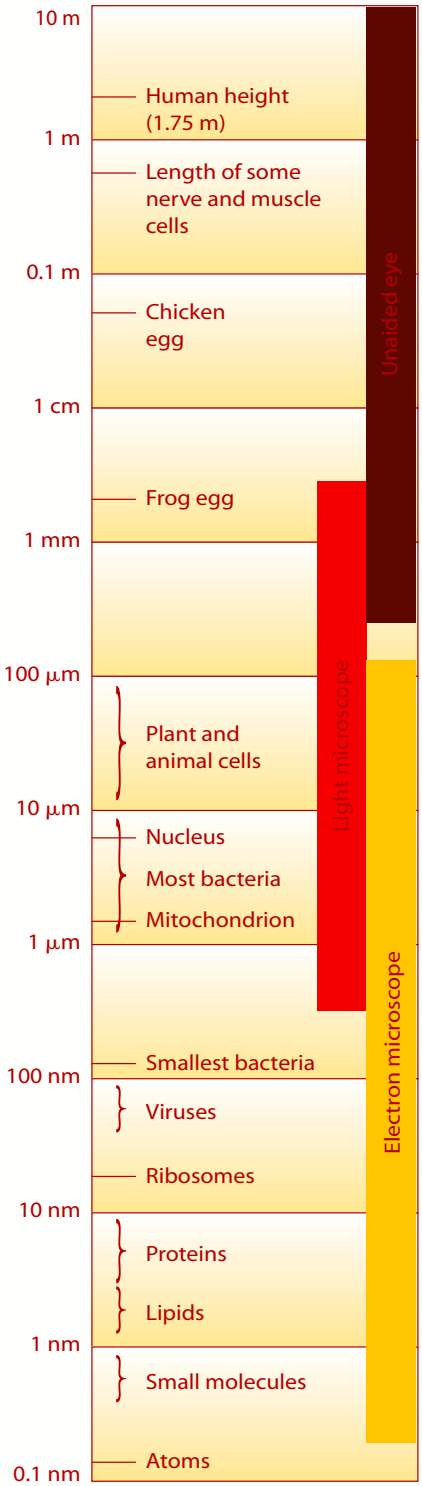


Figure 7.5

The relative sizes of various cells



Measurements

1 centimeter (cm) = 10^{-2} meter (m) = 0.4 inch
1 millimeter (mm) = 10^{-3} m
1 micrometer (μm) = 10^{-6} m
1 nanometer (nm) = 10^{-9} m

Eukarya are Protista, Plantae, Fungi and Animalia. The recent introduction of the "domain" level in taxonomy reflects the importance of cell structures and functions as criteria for classification.

Plant and Animal Cells

Fundamental differences in cell structure also exist between plants and animals. Plant cells have a **cell wall**, as well as **chloroplasts** (organelles that carry out photosynthesis). Many plant cells have a large fluid-filled organelle called the **central vacuole**, a water reservoir occupying much of the cell's interior. (see Figure 7.3) When the central vacuole is filled with water, the cell swells. Its plasma membrane bulges outward against the cell wall, creating **turgor pressure**. If a plant needs water, the central vacuole loses some of its water reserve and turgor pressure drops. Loss of turgor pressure in stem and leaf cells causes the plant to wilt. Animal cells lack cell walls, chloroplasts and central vacuoles. (see Figure 7.4) One thing to note is that both plant and animal cells have **mitochondria** (plural of mitochondrion), organelles for cellular respiration. Students first encountering this new information often successfully make the association between plant cells and chloroplasts, but then associate mitochondria only with animal cells. While chloroplasts are found only in the cells of plants and algae, mitochondria are found in all eukaryotes, including plants.

Why Cells Are Small

A final concept to address in this introduction to cells is the issue of cell size. With very few exceptions, cells are microscopic, their diameters measured in microns, millionths of a meter. (see Figure 7.5) An elephant

A Closer Look:

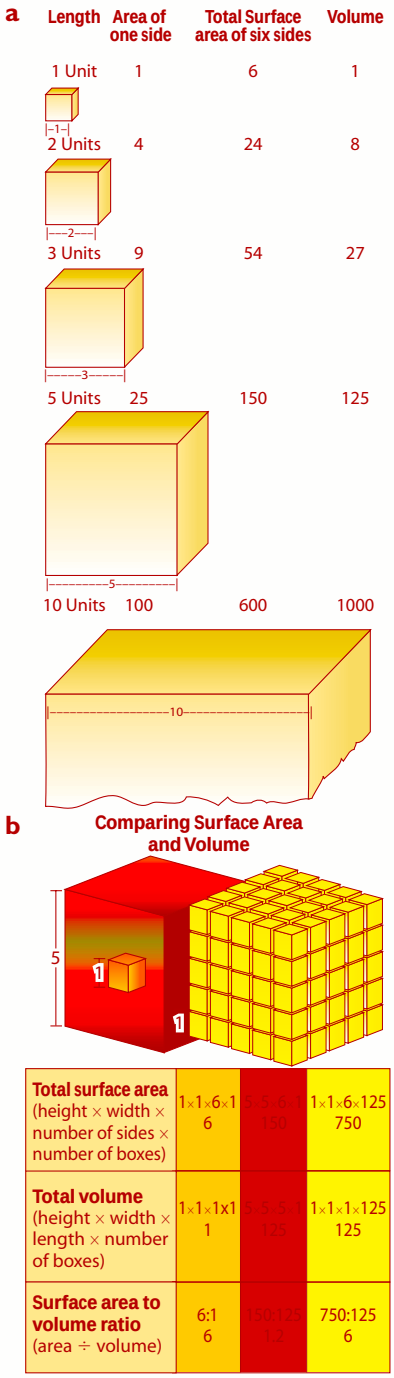
Drug Resistance in Cancer

As we have seen, membrane pumps are essential for cells to be able to draw important substances into their interior. They also serve to keep out harmful chemicals, and it is this function that can, in some circumstances, be turned against the body.

Cancer occurs when normal cells transform and begin to grow in an unregulated manner. Because cancerous cells are not foreign to the body, the human immune system is not always able to respond to and destroy them. Many patients must therefore undergo treatment with chemotherapy, which often involves the use of toxic drugs to disrupt the metabolic processes of cancer cells. Some cancer cells, however, are able to evade the effects of chemotherapy. These drug-resistant cells utilize their membrane pumps to expel the drugs before they can accumulate and exert their effects within the cells. Drug resistance is a major reason for the ineffectiveness of chemotherapy. Some cells can fend off more than one type of drug, making them multidrug resistant. It is a problem that is present in many types of cancer and affects virtually every available chemotherapy agent.

Two of the drug pumps that scientists have studied extensively are P-glycoprotein, also called MDR1 for "multidrug resistance," and MRP (multidrug resistance-associated protein). Several pharmaceutical companies are developing new compounds designed to overpower this defense mechanism. Most of these experimental drugs work by binding to the membrane pumps on the outside of the cancer cell. They are intended to be given in combination with standard anticancer drugs, disabling the pumps for long enough that the tumors are rendered sensitive to the chemotherapy. One biotechnology company is testing a drug intended to be used by itself: it is an anthracycline—a drug in the same class as the common agent doxorubicin—that is specially designed to evade P-glycoprotein and stay inside the tumor cell.

Figure 7.6
As solids increase in size, volume increases faster than surface area. Note in (**b**) how the 125 yellow boxes have the same volume as the blue box. However, the surface area of all the yellow boxes is five times greater than that of the blue box. The surface area to volume ratio between the red box and all the yellow boxes is the same.



might be forty times your mass, but its cells are the same size as your cells. The elephant just has more of them. Why are cells so small? Why aren't giant organisms made of giant cells? Do smaller cells have an advantage over larger cells, or is this some accident of evolution? Let's consider life at the level of a single cell and see if we can solve this riddle.

A cell's interior contains its nucleus and cytoplasm, where almost all its chemical reactions occur. At the level of a cell, life involves an enormous variety of chemical reactions. For these reactions to continue, a cell needs a steady supply of reactants. For example, to produce energy, a cell must continually take in sugar and oxygen. Conversely, many reactions produce waste materials, like the carbon dioxide and water released when sugar is broken down for energy. A cell must continually rid itself of wastes so they don't interfere with other chemical processes. Any material entering or leaving a cell must pass across the cell's plasma membrane. Therefore the plasma membrane must be extensive enough to take in sugars and other substances needed for all its metabolic processes. Similarly, the plasma membrane must be large enough to allow waste products to pass out of the cell and not build up inside.

Keeping all its metabolic needs in mind, let's imagine what would happen if a single cell began to grow. For the sake of simplicity, let's imagine our cell is spherical. If its diameter doubles, what happens to its surface area (plasma membrane) and volume (cytoplasm)? When diameter doubles, surface area doesn't double, but increases four times. This is because area is two-dimensional, so it is proportional to the square of the diameter. If the cell's diameter triples, its surface area increases by nine times (3^2). (see Figure 7.6 a) This might seem beneficial for the cell, because it provides more membrane surface area. But let's see what happens to the cell's volume as diameter increases.

As it turns out, volume increases even more rapidly. This is because volume is three-dimensional, so it is proportional to the cube of the diameter. If diameter doubles, volume increases by eight times (2^3). This means eight times as many chemical reactants, reactions and waste products. But surface area only increased by four times, yielding not nearly enough plasma membrane for everything to pass through. The difference is even more dramatic as diameter triples. Volume increases twenty-seven times (3^3), but surface area only increases nine-fold. So it seems cells are limited in size because of a mathematical relationship between surface area and volume—the plasma membrane and cytoplasm. As cytoplasm increases, the plasma membrane doesn't keep up, causing the cell to fail to function. Biologists call this relationship the **surface to volume ratio**. (see Figure 7.6 b) In small cells, this ratio is high, but it drops as a cell increases in size because surface area increases more slowly than volume. Cells can grow somewhat larger by remaining flat or thread-like rather than spherical, because those shapes only increase slightly in overall volume. (see Figure 7.7)

Internal transport, moving substances around within cells, also becomes a problem as cells become larger. The cell's interior gets farther from the plasma membrane, and life-sustaining reactants become spread out. As you will learn in the next section, extensive internal membranes partition the cytoplasm of eukaryotic cells. These membranes create passageways and channels to concentrate and direct the internal movement of many

materials. Similar evolutionary developments have occurred in multicellular organisms, such as structural features that increase surface area in the internal organs of many animals. For example, millions of tiny air sacs inside your lungs ensure ample intake of oxygen for the entire body. Your circulatory system solves the problem of carrying materials throughout the body by using a great many tiny capillaries instead of fewer larger vessels. Numerous small, flattened red blood cells carry oxygen more effectively than a smaller number of larger, more spherical cells could. Smaller cells have more total surface area than the same overall volume of larger cells. This allows more oxygen to diffuse across the cells' membranes.

Both external and internal selective pressures have influenced the evolution of multicellular organisms. External adaptations help shape an organism to better fit its environment. Internal adaptations, like structures within cells and organs, help organisms meet their metabolic needs. Both are tied to the conceptual theme of structure and function, a theme applying equally to molecules, cells and entire organisms.

7.1 Check Up

1. Compare and contrast prokaryotic and eukaryotic cells. To which "category" do each of the three domains and six kingdoms belong?
2. All cells possess three fundamental characteristics. Describe those three characteristics and define the role of each in the cell. Include a sketch of a eukaryotic cell. Label all parts as found in Figures 7.3 and 7.4.
3. Explain what happens to the surface area and volume of a cell as it increases in size. What problems occur as the cell grows, and how does the surface to volume ratio limit how large a cell may become? Examine potential "remedies" cells often use to avoid this effect.
4. Compare and contrast the structure and function of a virus to a cell.

7.2 The Nucleus and Other Organelles

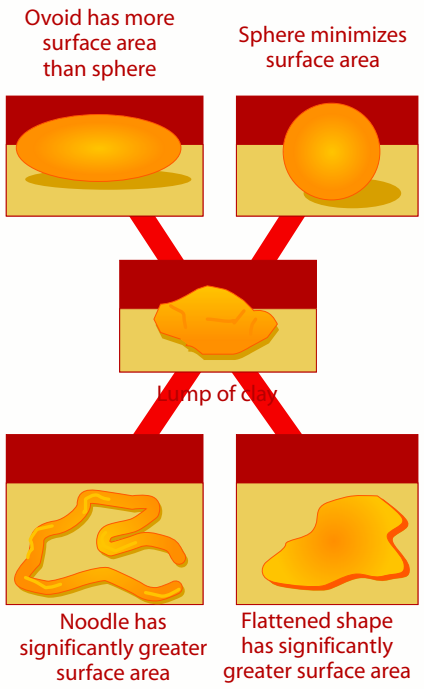
Cells are mostly made up of carbohydrates, proteins, lipids and nucleic acids, along with smaller organic building blocks, ample water, some ions and minerals. But how is such an array of molecules organized in a living cell? In Chapter 5 you read about the role of enzymes as cellular catalysts, which either cause or speed up reactions inside cells. Enzymes are proteins that directly use and manipulate the other molecules of cells. These proteins build up and break down lipids, amino acids, carbohydrates, nucleic acids and other molecules. But DNA is the molecule directing the construction of proteins, thereby indirectly controlling the cell's overall structure and function. In eukaryotic cells, DNA is located inside the nucleus, which is sometimes called the cell's control center.

The Nucleus

The nucleus is surrounded by the **nuclear envelope**, a pair of lipid bilayers containing a number of proteins that perform various functions. Among these functions is the regulation of materials passing in and out of the nucleus. For example, certain hormones control growth and other body functions when they enter the nucleus and interact with the DNA. (DNA's

Figure 7.7

Shape also affects surface area.



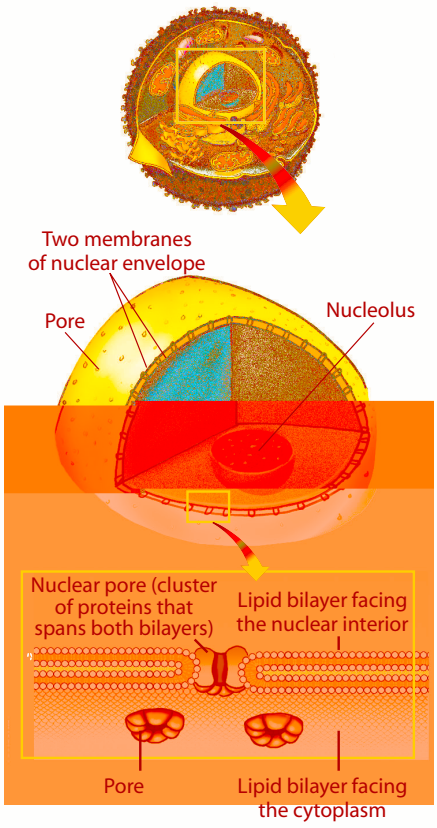
Area and Volume of a Sphere

Area of a sphere = $4\pi r^2$
Volume of a sphere = $4/3\pi r^3$
If the radius increases by a factor of 6, the area increases by a factor of 36 and the volume by a factor of 216.

7.2 Objectives

- Analyze and define the structures and functions of various eukaryotic organelles.
- Compare and contrast the structure of eukaryotic and prokaryotic cells.

Figure 7.8
The nuclear envelope surrounds the nucleus, the control center of the cells.



structure and function is the topic of Chapter 11.) When a DNA "blueprint" is used to make a protein, an RNA copy is first made from the DNA. The RNA copy then leaves the nucleus, where it is used to direct protein synthesis. This process is like going to the library for information to help write a paper or do a household project. If you don't need an entire book, you photocopy the few pages you do need for your personal use and leave the book in the library. The entire book is like the nuclear DNA, the photocopy is the RNA and the library door is a special opening in the nuclear membrane allowing you to enter and leave. (see Figure 7.8) The outer membrane of the nuclear envelope forms a continuous network with the cell's **endoplasmic reticulum**, a system of membranes that partition the cytoplasm for increased efficiency of cell functions. When a cell is actively growing, small structures sometimes form within the nucleus. Each of these is a **nucleolus**, containing RNA and protein molecules used to assemble ribosomes, which build the cell's proteins. (see Figure 7.9)

Organelles

Aerobic cellular respiration and photosynthesis, perhaps the two most important metabolic processes on Earth, are performed by two organelles, mitochondria and chloroplasts. Since these reactions are the subject of much of the next chapter, we'll only introduce the organelles here.

Mitochondria

Mitochondria are responsible for the majority of cells' adenosine triphosphate (ATP) production. As you learned in Chapter 6, mitochondria are the size of bacteria (1-5 μm) and contain their own DNA, reproducing independently of the cell. Mitochondria have a double-membrane structure. The outer membrane is the smooth outer covering for the organelle, while the inner membrane is arranged into numerous folds called **cristae** (plural of crista), increasing the membrane's surface area. (see Figure 7.10) This is an important structural feature, because the chemical reactions forming ATP occur within the inner membrane. The extensive folding allows mitochondria to perform many more reactions than a simple, unfolded membrane could.

Chloroplasts

Chloroplasts are found only in plant cells and algae. Like mitochondria, chloroplasts have their own DNA and reproduce independently. They also have inner and outer membranes. The inside of a chloroplast is partitioned into many flat, disc-shaped structures called **thylakoids**. (see Figure 7.11) Like other flattened structures, the shape of thylakoids increases their surface to volume ratios. Thylakoid membranes contain **chlorophylls**, green pigments used to capture light energy during photosynthesis. The inner membranes of mitochondria and chloroplasts contain similar proteins and carry out similar reactions.

The Endomembrane System

The cytoplasm of eukaryotic cells is partitioned into smaller areas by the endomembrane system, a network of folding membranes and pockets specialized for certain functions. The most extensive portion of this system is the endoplasmic reticulum, or ER. (see Figure 7.12) Some ER appears roughly textured because it is speckled with ribosomes, tiny

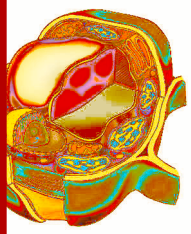


Figure 7.13

Golgi bodies package materials for secretion from the cell. (**1**) RNA instructions for building polypeptides leave the nucleus. (**2**)RNA is translated into protein in the RER. (**3**) The protein products are carried in vesicles to the Golgi body. (**4**) The protein products pass through the Golgi body and prepare for secretion from the cell. (**5**) The vesicles fuse with the cell membrane and release the protein.

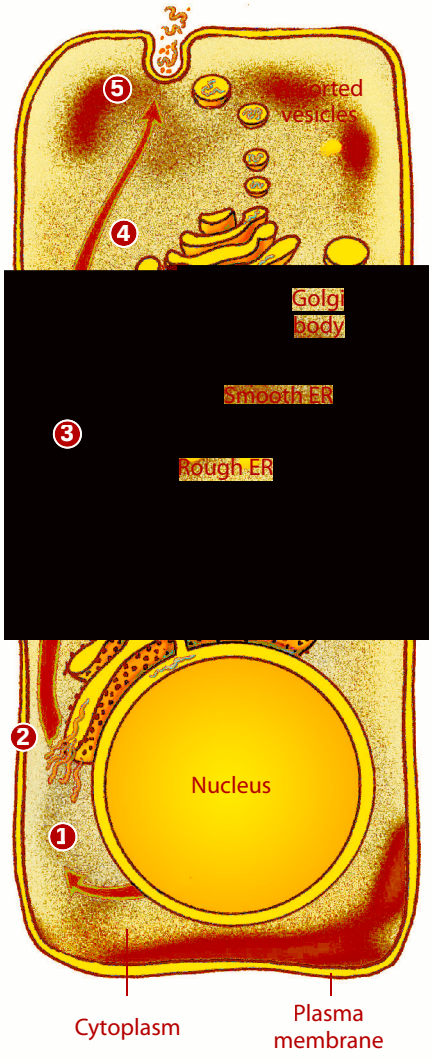
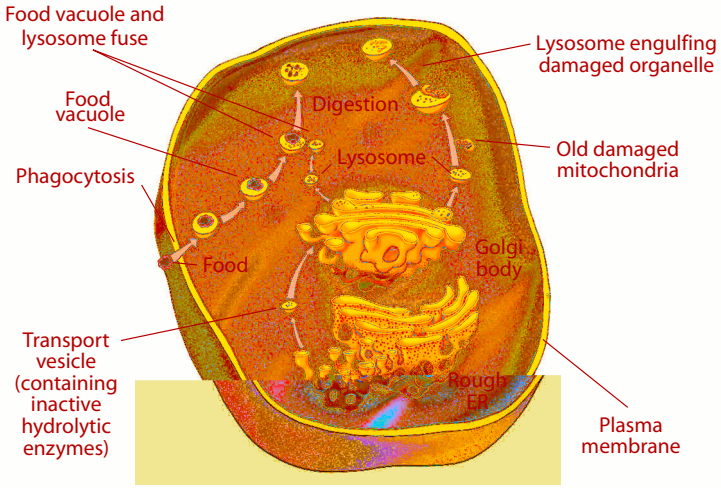


Figure 7.14

Food vacuoles and lysosomes are cells' digestive structures.



organelles that synthesize proteins. This is called **rough endoplasmic reticulum**, or RER. Rough ER often connects directly to the outer layer of the nuclear envelope, allowing RNA molecules leaving the nucleus to immediately interact with ribosomes to build proteins. Rough ER appears as multiple layers of thin sac-like structures. Rough ER layers farthest from the nucleus produce small membrane sacs called **vesicles**. Vesicles are like little fluid bubbles that carry newly formed proteins through the cytoplasm to a **Golgi body** or other part of the endomembrane system. Golgi bodies package proteins for secretion from a cell. Molecules passing through the membrane layers of a Golgi body are modified as they pass through each chamber. After leaving the last layer, they are wrapped in Golgi membrane, forming a vesicle to carry the material to the plasma membrane, where it leaves the cell. (see Figure 7.13) For example, digestive enzymes made by cells lining your stomach are released from those cells to help digest food you eat. **Smooth endoplasmic reticulum**, SER, appears smooth because it lacks ribosomes. The smooth ER has an appearance like a complex network of interconnecting tubes. Cells synthesize lipids inside the smooth ER. (refer to Figure 7.12 on page 203)

Lysosomes are small membrane-bound vesicles that aid cellular digestion. For example, amoebas sometimes engulf bacteria or other entire cells when they feed, containing the cells in **food vacuoles**. The amoeba's digestive enzymes are contained within lysosomes, which form at a Golgi body and fuse with the food vacuole. (see Figure 7.14) This allows digestion of the "swallowed" cell to occur. The final vesicles to mention are **peroxisomes**, tiny sacs in which fatty acids and amino acids are broken down. During this process, highly reactive hydrogen peroxide (H_2O_2) is produced, but quickly broken down by enzymes. Figure 7.15 summarizes the functions of several vesicles.

Although bacteria (prokaryotic cells) lack organelles to carry out metabolic functions, many do have specialized internal membranes in which some reactions take place. Most notable are respiratory membranes, formed by numerous infoldings of the plasma membrane. These not only resemble the highly folded inner membranes of mitochondria, but also

Figure 7.15

A brief summary of some organelles and vesicles and their functions

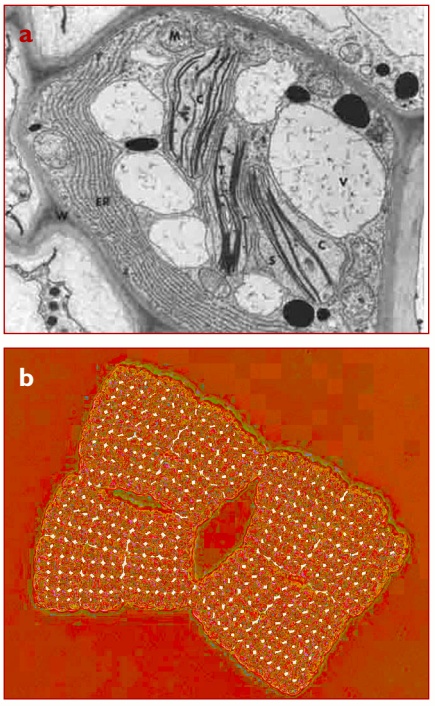
Cell Structure	Function
Chloroplast	Found only in plants and some plant-like protists; carries out photosynthesis
Food vacuole	Forms when a cell "swallows" a smaller cell during endocytosis
Golgi body	Part of the endomembrane system; processes and prepares molecules for release from the cell
Lysosome	Small vesicle containing enzymes; fuses with food vacuoles and helps the cell to digest food items
Mitochondrion	Found in almost all eukaryotic cells; location of most ATP synthesis in cells
Nucleolus	Small structure within the nucleus responsible for assembling ribosome parts
Nucleus	Contains the cell's DNA and chromosomes
Peroxisome	Small vesicle that breaks down fatty acids, amino acids and hydrogen peroxide
Ribosome	Tiny structure made up of RNA and proteins; some are located within the RER, others are free within the cytoplasm; location of protein synthesis
Rough endoplasmic reticulum	Part of the endomembrane system containing many reticulum ribosomes, hence its rough appearance; location of protein synthesis and distribution throughout the cell
Smooth endoplasmic reticulum	Part of the endomembrane system formed of many interconnecting tubules running throughout the cytoplasm; location of lipid synthesis for the cell
Vesicle	Small membrane-bound sac that carries substances around within the cell as well as to the plasma membrane for release from the cell

carry out the same metabolic reactions. Internal membranes similar to those of thylakoids are found inside cyanobacteria, a group of bacteria that carry out photosynthesis. Cyanobacteria cells resemble the chloroplasts of plant cells, both in structure and in function. (see Figure 7.16)

When you look at photographs and drawings of these organelles, it's very easy to lose sight of exactly how tiny and delicate these structures actually are. Diagrams of cells and their membranes often look like slices of a basketball with a tough, leathery hide. Internal membranes and organelles resemble splashing liquids and funny-shaped balloons. But a cell's various membranes are made of thin bilayers of lipid molecules, more delicate than the film of a soap bubble. When vesicles bud from a Golgi body, or merge with a food vacuole or plasma membrane, the actual event is much like soap bubbles dividing or merging. For these tiny organelles, lipid membranes are strong enough to hold their contents, like soap bubbles are strong enough to contain an air pocket. At the molecular level, forces of attraction between membrane molecules are greater than the weight of the materials they contain within the cell's cytoplasm. It's all a matter of scale.

Figure 7.16

Chloroplasts are thought to be descended from cyanobacteria. (**a**) chloroplast (**b**) cyanobacteria



7.2 Check Up

1. Trace the path of a protein in a eukaryotic cell from its genetic material to its exit from the cell. Include the functions of all the organelles involved in this microscopic journey.
2. Describe the structural complexities and functional roles of both mitochondria and chloroplasts. How do the structure and function of these organelles relate to the theory of endosymbiosis?
3. Compare the way prokaryotes and eukaryotes carry out metabolic functions. How are the metabolic functions of prokaryotes related to the theory of endosymbiosis?

7.3 The Plasma Membrane

7.3 Objectives

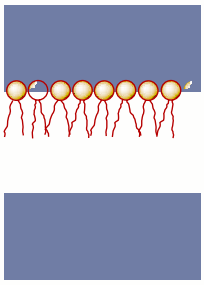
- Describe the structure of plasma membranes and explain lipid bilayer formation.
- Distinguish between integral and peripheral proteins.
- Differentiate between transport, marker and receptor proteins.

The plasma membrane performs a number of vital roles in the cell. It defines the edge or boundary of the cell, separating the cytoplasm from the environment. Perhaps its most important role is regulating substances entering and leaving the cell. Biologists have discovered the plasma membrane is made up of a number of macromolecules with different functions, rather than being a uniform, homogeneous structure. Although this section will focus on the plasma membrane, other cellular membranes, like ER and mitochondrial membranes, have the same general structure. Specific proteins give various membranes their different properties and functions, since phospholipids vary little in structure.

Phospholipids Revisited

A bilayer of phospholipid molecules forms the overall structure of a plasma membrane. Phospholipids have a polar hydrophilic ("water-loving") head and two nonpolar hydrophobic ("water-fearing") fatty acid tails. You learned in Chapter 5 that phospholipids will spontaneously form a bilayer when they are mixed into an aqueous (water) solution. (This is because water molecules repel the hydrophobic tails, which weakly attract each other.) If the fatty acid tails are mostly saturated, the lipid molecules will have stronger attractions to each other, making the membrane slightly less fluid. More unsaturated fatty acids allow greater freedom of movement of the membrane molecules. (see Figure 7.17) Cholesterol molecules within the layers help stabilize the membrane.

Figure 7.17



Proteins in Cell Membranes

Several types of proteins are associated with membranes. (see Figure 7.18) **Integral proteins** extend through both lipid layers, from cytoplasm to environment, while **peripheral proteins** are found only at the hydrophilic surfaces. Many of these proteins are capable of lateral (sideways) movement within the lipid bilayer. The image created is like boats on a lake. They are free to move about on the surface, but unless something goes seriously wrong, they will remain upright, not turning somersaults in the water or sailing upside down. Similarly, proteins don't normally flip-flop within the membrane, but many are capable of "sailing" about. The picture created of moving molecules and a dynamic membrane is called the **fluid mosaic model**. (see Figure 7.19) It is fluid because lipids and many proteins can freely move about the membrane. It's a mosaic because the membrane is made up of many small pieces working together as one structure.

While the lipid portion of the membrane forms a thin barrier, membrane proteins carry out a variety of functions for the cell. **Transport proteins** allow substances dissolved in the cytoplasm or the cell's environment to pass through the membrane. (see Figure 7.20) Without the help of these proteins, most substances would not be able to pass in and out of cells. Several types of transport proteins will be described in the next section.

Figure 7.18
The plasma membrane and its many proteins

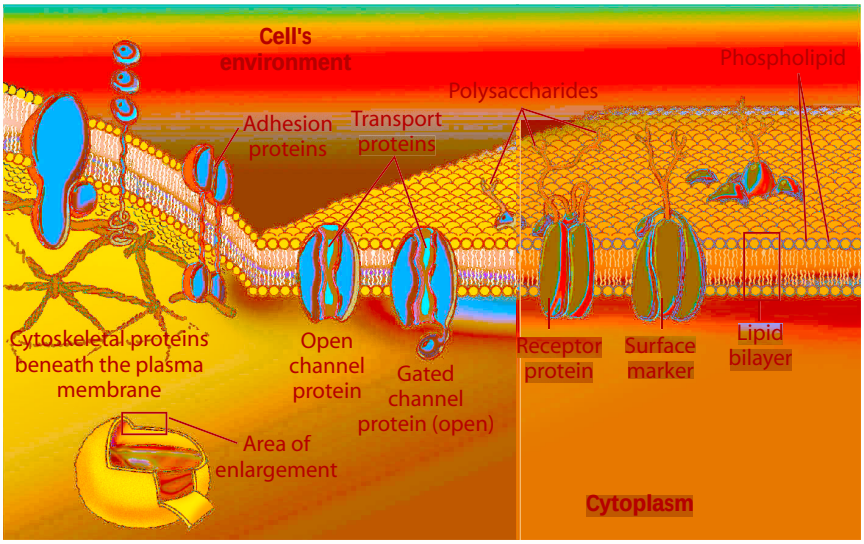
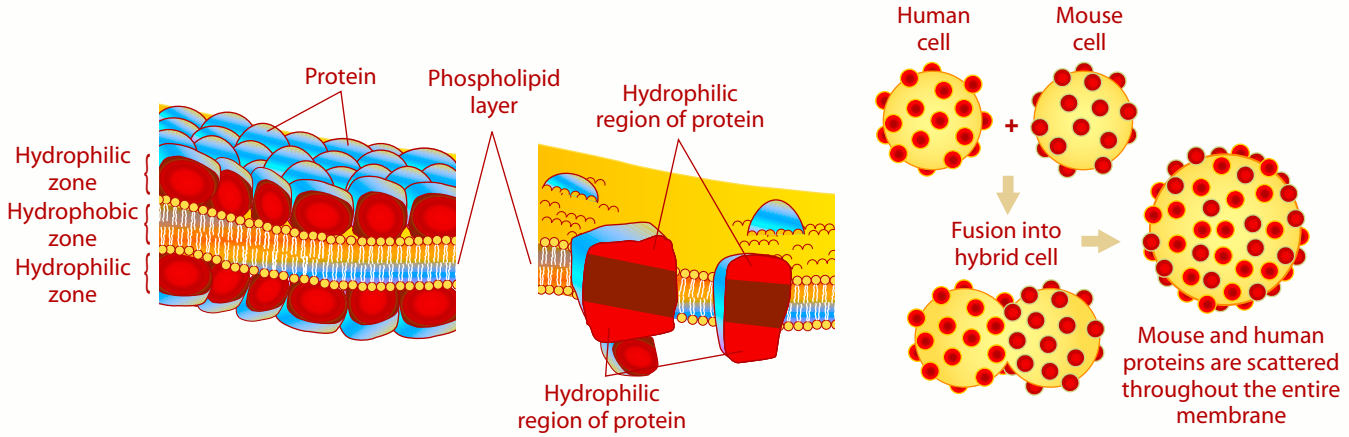


Figure 7.19

(**a**) The old "sandwich model" of a cell membrane was disproven

(**b**) The current fluid mosaic model

(**c**) Hybrid cells revealed the fluid nature of membranes.



On the outer surface of cells, **marker proteins** are important in cell identification and recognition. Cell markers are **glycoproteins**, protein molecules with attached carbohydrates. One important function of marker proteins is the cellular recognition mechanism of your immune system. All the cells of your body have markers identifying them as *your* cells. Immunologists (scientists who study the immune system) call this recognition of "self." White blood cells of your immune system recognize your "self" markers and leave those cells alone. However, cells with foreign markers are interpreted as "nonself" and are subject to attack. This mechanism is responsible for the identification of bacteria and viruses that invade the body and potentially cause illness. (see Figure 7.21 on the next page)

Figure 7.20
Proteins help move materials in and out of cells.

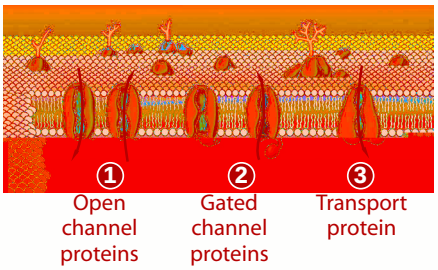


Figure 7.21

Surface markers identify cells.

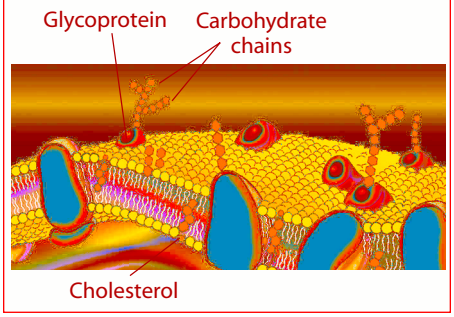
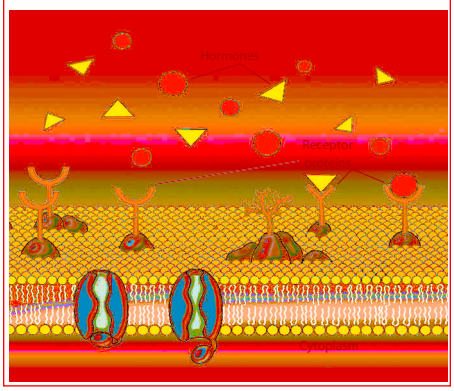


Figure 7.22

Receptor proteins pick up specific substances in a "lock and key" manner.



You may also be familiar with human ABO blood types. The different blood types represent blood with different marker proteins on its red blood cells. Type A blood has "A" markers, type B has "B" markers and type O has neither. The "O" really means "zero" and indicates a lack of both A and B markers. Marker proteins also determine tissue matches between donors and recipients for organ transplants. In transplant operations, if a good match isn't found, the recipient's immune system will identify the transplanted organ as "nonself" and attack (reject) it. Even when close matches are found, organ recipients take medications to suppress the immune system and prevent organ rejection. Unfortunately, this also makes the recipient more susceptible to common illnesses easily fought by a normally functioning immune system.

Receptor proteins on the plasma membrane bind to substances in the cell's environment. A common example of receptor function is the binding of hormones to their target cells. For example, insulin and glucagon are hormones that regulate the concentration of glucose in the blood. They are made and released by the pancreas and carried by blood throughout the body. Cells with surface receptors for these hormones are in the liver, the organ storing excess glucose and releasing it when it's needed. (see Figure 7.22) When certain liver cell receptors "catch" glucagon molecules, changes are triggered in those cells, causing them to release glucose into the blood. Other organs don't respond to this hormone because they lack proper receptors.

The specific functions of proteins are closely connected to their three-dimensional structures (their conformations). The three types of membrane proteins described earlier are no exception. Protein conformation also explains the recognition of cell markers by the immune system, as well as the fit between hormones and their receptors. The "lock and key" analogy is sometimes useful to help visualize the fit between a hormone and its receptor. Similar molecular matches explain why most viruses attack very few host organisms, or even only a specific organ. For example, cold viruses attack mucous membranes of your nasal passages and HIV only attacks certain white blood cells (helper T cells). Viral proteins and surface proteins of the affected individual's cells must "match" in shape for the virus to attach to and enter a host cell.

7.3 Check Up

1. Describe the structure of phospholipids and explain how bilayer formation occurs. Be sure to include the roles cholesterol, integral proteins and peripheral proteins play in the structural integrity of the plasma membrane.
2. Examine the differences between transport, marker and receptor proteins of cells. How is structure related to function in regard to these protein types?
3. Explain how the "lock and key" analogy is appropriate when explaining the relationship between receptor proteins and hormones.

Figure 7.25

In many nerve cells, K^+ ions diffuse outward and Na^+ ions diffuse inward due to their relative concentrations inside and outside the cell.

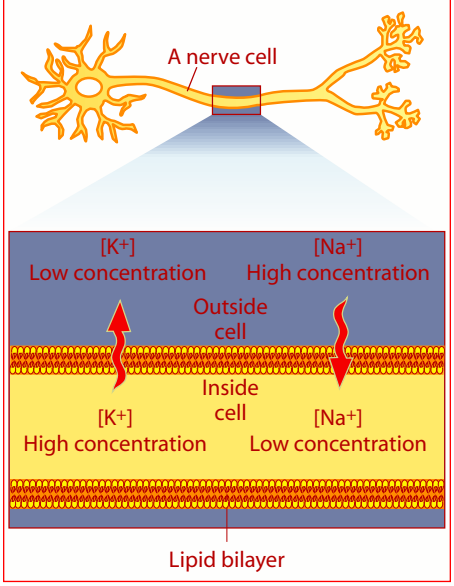
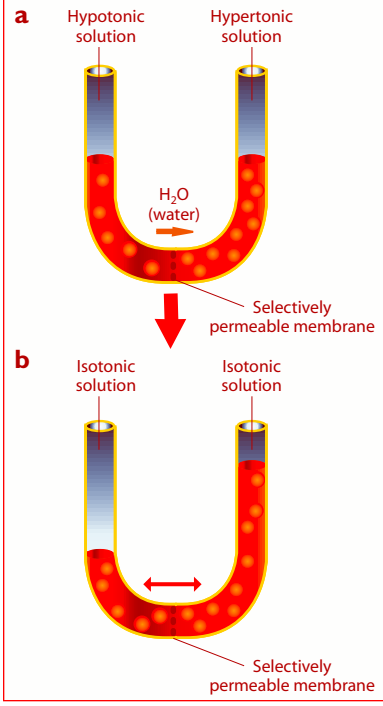


Figure 7.26

(**a**) During osmosis, water moves across a membrane from an area of high water concentration to one of low water concentration. (**b**) When solutions reach equilibrium (become isotonic), osmosis occurs at the same rate in both directions.



breeze, and stirring a drink allows sugar to dissolve more rapidly. Stirring the same amount of sugar in a hot drink allows it to dissolve even more rapidly because molecules move more rapidly at higher temperatures.

How does all this apply to cells? The simplest way a substance can enter or leave a cell is simply to diffuse through the lipid bilayer. This only works for a few substances. Tiny gas molecules like oxygen and carbon dioxide move through the lipid bilayer quite easily. Water molecules are also small enough to squeeze through the membrane. Steroid hormones are larger but are lipid-soluble (meaning they dissolve in oil but not in water), so they also pass through a lipid bilayer. (see Figure 7.24) In all these cases, molecules *can* diffuse through the membrane, but when *do* they pass through? What force actually moves them across? If you apply the idea of diffusion you should be able to answer these questions. The molecules move down a concentration gradient. If a substance is in greater concentration inside the cell, it will diffuse outward. If a greater concentration exists outside, it will diffuse inward. (see Figure 7.25) When molecules move through membranes on their own, with no energy boost from the cell, the process is sometimes called **passive transport**.

Osmosis

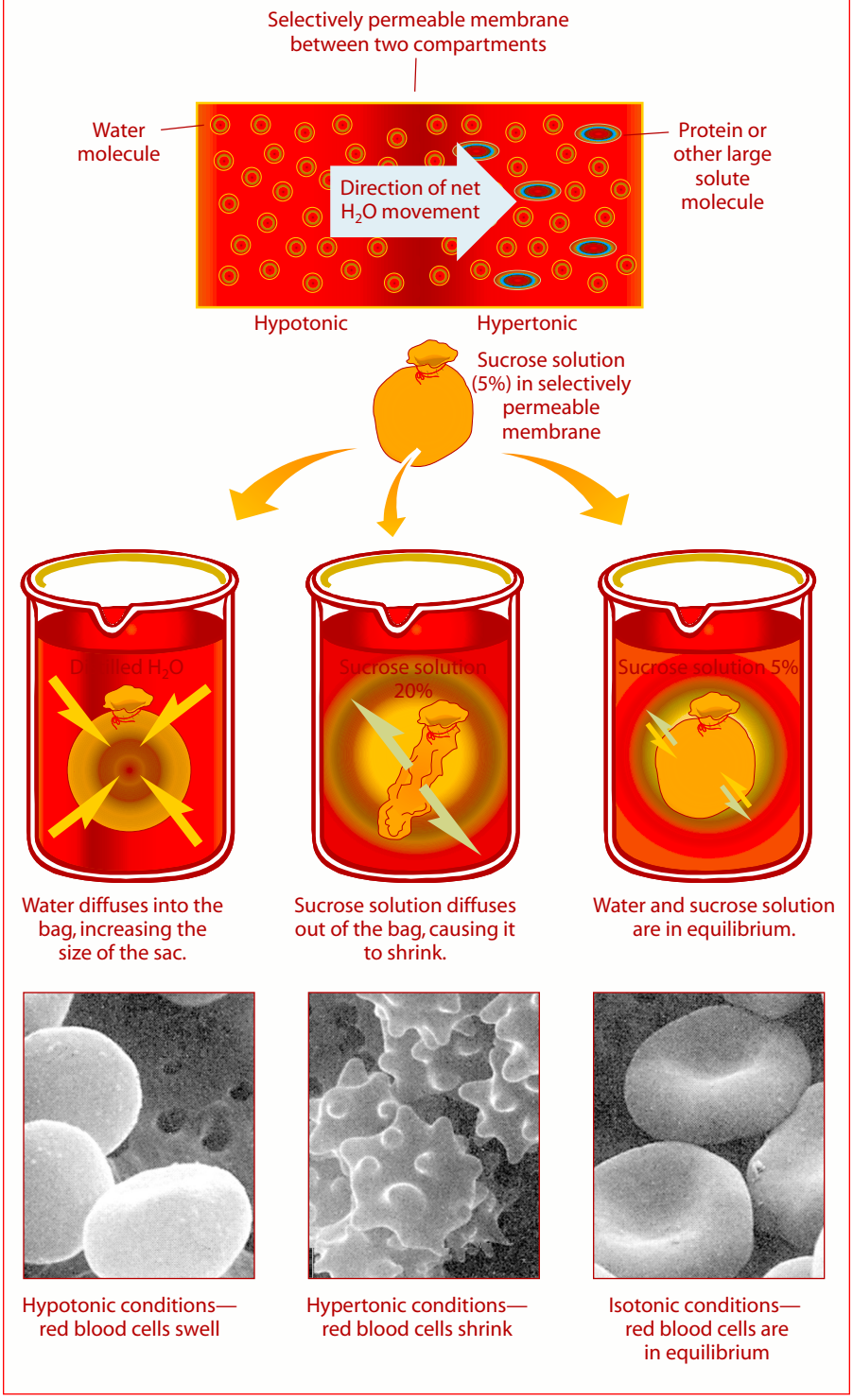
Osmosis is a special case of diffusion. Osmosis is the diffusion of water across a membrane down a concentration gradient. Just as water always flows downhill, it always moves down concentration gradients—from greater to lesser water concentration. This can be confusing at first because we're referring to water concentration, not the concentration of solutes.

Let's use a specific example by comparing saltwater and freshwater. Saltwater obviously has a greater solute (salt) concentration than freshwater. When one solution has a greater solute concentration than another, it is **hypertonic** compared to the "weaker" solution. *Hypertonic* simply means "more solute." Therefore saltwater is hypertonic to freshwater. Another term can be used to describe freshwater compared with saltwater. We can say freshwater is **hypotonic** to saltwater. *Hypotonic* means "less solute." Now, in your mind, imagine mixing a beaker of saltwater and a beaker of freshwater. Swirl them together in one beaker, then divide the solution into two beakers again. This time, both solutions have the exact same solute concentration, because they were mixed together. When two solutions have the same solute concentration, we call them **isotonic**, meaning "equal solutes." (see Figure 7.26) Note that pure water is hypotonic when compared to any other aqueous solution. Pure water has the highest possible water concentration because it isn't mixed with anything.

How does all this solute concentration business affect osmosis? If a cell were compared to a freshwater environment, the cell would be hypertonic to its surroundings due to its ions, sugars and other solutes. Water moves down a concentration gradient by osmosis from the freshwater environment into the cell which has many cell solutes. (see Figure 7.27) Water always diffuses from the purer region into one with a higher solute content.

Figure 7.27

Water moves from high water concentration to low water concentration. We could also say water moves from a hypotonic to a hypertonic environment.



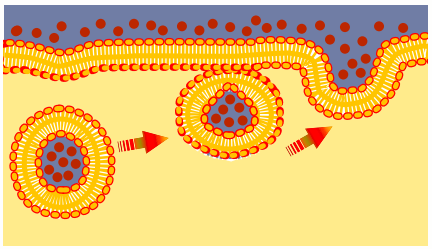
these membrane pumps, along with facilitated transport channels, to maintain proper solute concentrations across their membranes. Curiously, no known cellular mechanism exists to actively transport water. Cells move water in or out by actively transporting solutes to one side of the membrane, thus creating a locally hypertonic condition. Water will then follow the pumped solutes by osmosis. (see *A Closer Look: Drug Resistance in Cancer* on page 199)

Endocytosis and Exocytosis

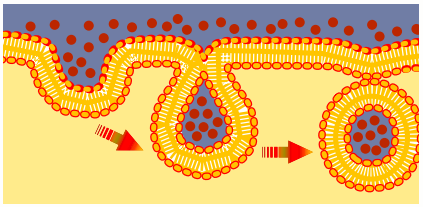
Some molecules and particles are too large to pass through membrane channels. To move these larger objects, cells form vesicles by the processes of endocytosis and exocytosis. In endocytosis, a pocket or indentation forms in the plasma membrane. As the pocket deepens, its outer edge or rim closes behind it, pinching off a vesicle into the cytoplasm. (see Figure 7.30) Endocytosis generally happens in one of three ways:(m0 Teast seolectivs formsis)

Figure 7.31

a Exocytosis



b Endocytosis



much more selective, as small clusters of receptor proteins line small indentations within the plasma membrane, allowing uptake of specific materials. **Phagocytosis** is the third mode of endocytosis. In phagocytosis, a larger cell actually engulfs large food particles or even another cell. Amoebas and some other protists "eat" in this manner. Certain white blood cells attack and destroy bacteria in the same way. Incoming material is carried in a membrane-bound food vacuole, which fuses with lysosomes in the cytoplasm. Enzymes in the lysosomes break down the ingested debris or cell, allowing nutrients to diffuse in the cell's cytoplasm.

Exocytosis is the opposite process of endocytosis. In exocytosis, material contained in vesicles within a cell's cytoplasm is released as the vesicles fuse with the plasma membrane and open to the cell's environment. (see Figure 7.31) This process occurs in many types of cells, including some in your nervous system, which release signaling chemicals called neurotransmitters. These chemicals diffuse across a tiny gap to the next cell, where they bind to membrane receptors. This is how nerve cells, which are not in direct physical contact with one another, transmit signals.

7.4 Check Up

1. A student fills two 55-gallon aquariums with water, allowing one to remain at room temperature (22°C), while heating the water of the other aquarium to 32°C. She then carefully places 5 mL of concentrated red dye in the corner of each aquarium, being careful not to agitate the water in the process. Predict what she will observe in the two aquariums over the next 10 minutes and explain your reasoning.
2. Red blood cells are placed into two different test tubes—one containing a 15% NaCl (sodium chloride) solution, the other distilled water. Describe the direction of water movement in this experiment and the effects it would have on the cells in each test tube. (The NaCl solution is hypertonic to the blood cells.)
3. Compare and contrast facilitated diffusion and active transport.
4. Explain why endocytosis and exocytosis might be used by a cell rather than simple diffusion, facilitated diffusion or active transport.

7.5 The Cytoskeleton

7.5 Objectives

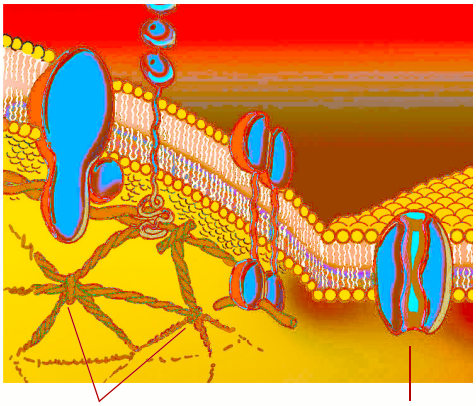
- Describe the structural and functional role of the cytoskeleton.
- Analyze the 9+2 structure of eukaryotic cilia and flagella.
- Compare and contrast prokaryotic and eukaryotic flagella.

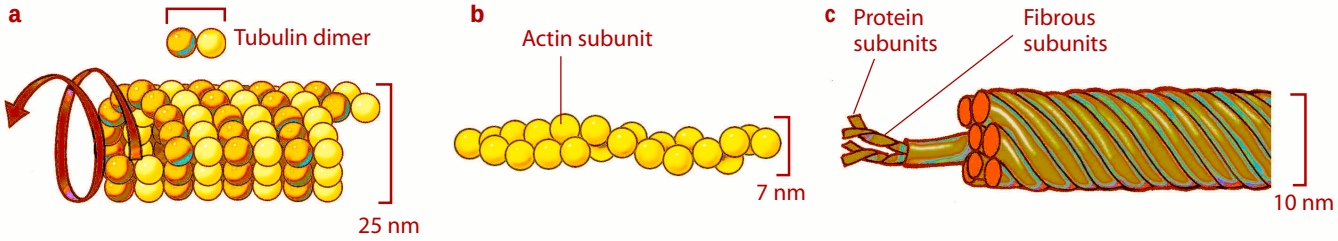
You may have formed an impression from the previous section that the cell's membranes are fairly weak and insubstantial. After all, the membrane is described as "fluid," with many of its molecules freely moving about. Does this make you wonder what holds your cells together? If all those lipid-coated cells just slide around, why aren't we all just big oily puddles on the floor? Fortunately, part of a cell's structure is much tougher than the lipid membrane. Just as a tent is shapeless and nonfunctional without its poles, the **cytoskeleton** gives a cell shape and strength and even helps it move.

A cell's cytoskeleton stretches from the nucleus to the plasma membrane in a complex scaffolding of structural protein molecules. These proteins are in the form of **filaments** and **microtubules**. (see Figure 7.32)

Figure 7.32

(**a**) Protein microtubules are hollow tubes made of spherical protein subunits (tubulin dimers in this example).
(**b**) Actin is a microfilament made of two twisted chains of spherical subunits.
(**c**) Intermediate filaments are made of several twisted strands of fiber-like proteins.





Property	Microtubules	Microfilaments (Actin filaments)	Intermediate filaments
Structure	Hollow tubes; wall is of tubulin proteins	Two intertwined actin strands	Fibrous proteins coiled into thicker cables
Diameter	25 nm with 15-nm center	7 nm	8-12 nm
Protein subunits	Alpha-tubulin and beta-tubulin	Actin	One of several different proteins of the keratin group
Functions	Maintain cell shape	Maintain cell shape	Maintain cell shape
	Cell motility (in cilia and flagella)	Muscle contraction	Anchor nucleus and other organelles
	Chromosome movements during cell division	Cell motility (pseudopods)	
	Organelle movements within cytoplasm	Cell division (forms cleavage furrow)	

Since these structural elements are proteins, they are manufactured inside the cell from instructions in the DNA. Many of the filaments and microtubules are anchored to proteins in the nuclear envelope and plasma membrane. As various cytoskeletal elements lengthen and shorten by the addition or removal of protein units, a cell will change shape, its fluid plasma membrane easily flexing to accommodate the changes. This is how amoebas and other similar cells form pseudopods to move and engulf food particles during phagocytosis. Similarly, portions of the cytoskeleton often control internal movements of organelles. The

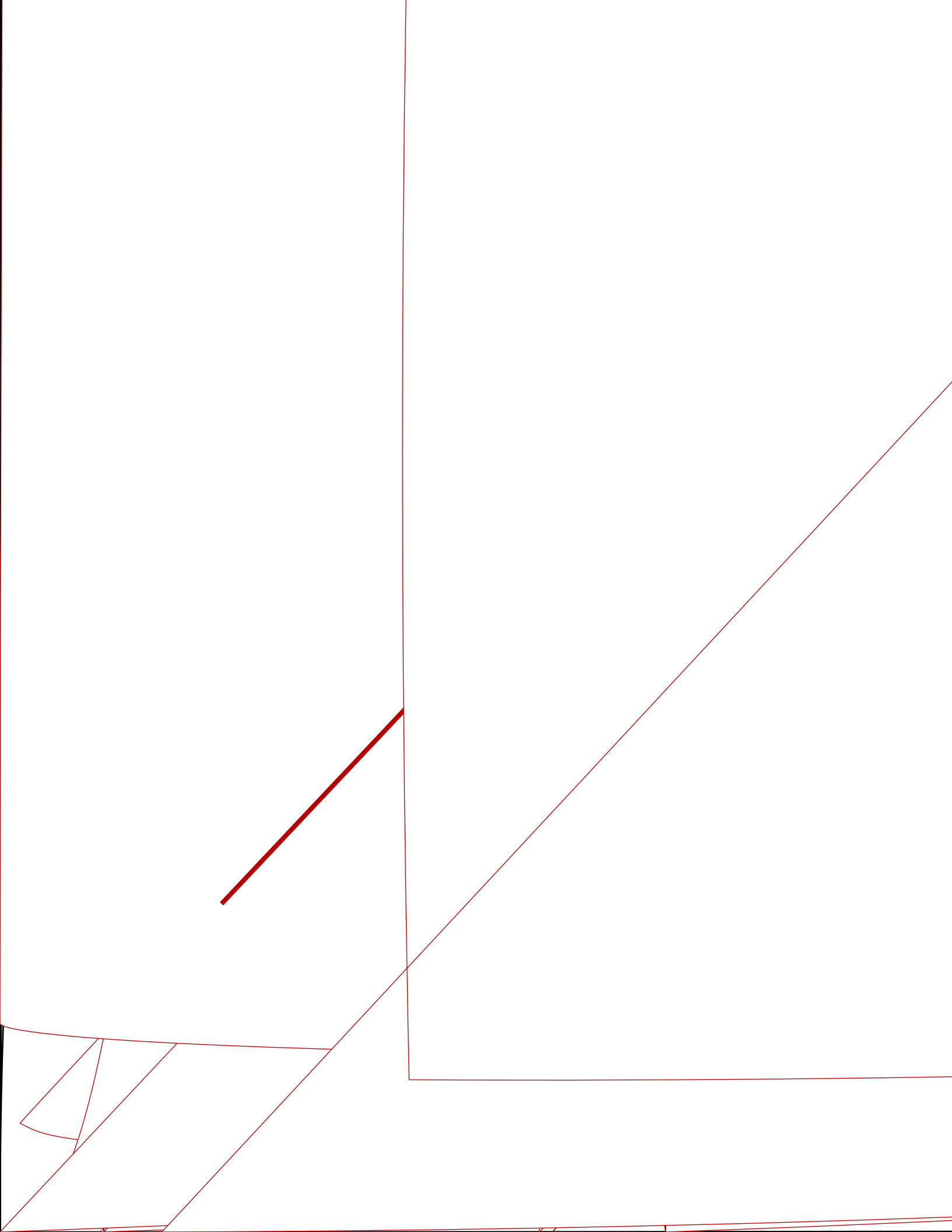
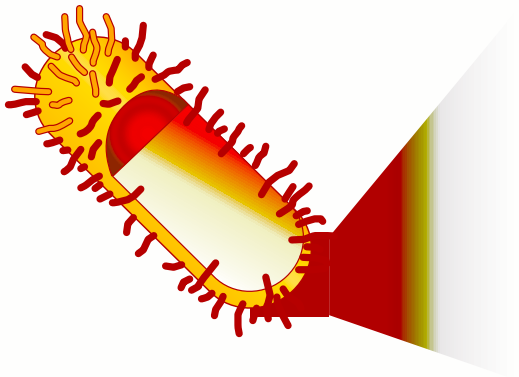


Figure 7.35



all eukaryotic flagella. Instead they are made of protein tightly packed into a somewhat rigid helical (corkscrew) shape. Attachment to the cell membrane is through the bacterial cell wall via a system of disk- and ring-shaped structures making up the **basal apparatus**. (see Figure 7.35) The flagellum moves as the basal apparatus rotates within the cell wall, turning the entire structure. In contrast, the eukaryotic flagellum is a hollow, flexible, membrane-enclosed structure, which moves by bending back and forth.

7.5 Check Up

1. Suppose a cell is unable to manufacture its cytoskeletal proteins. Predict what impacts this will have on the cell.
2. Summarize the structures and functions of microtubules, microfilaments and intermediate filaments.
3. Compare and contrast the structure of eukaryotic and prokaryotic flagella.
4. Draw a sketch of a typical prokaryotic cell and label the following parts: DNA, cytoplasm, ribosomes, plasma membrane, cell wall and flagella.

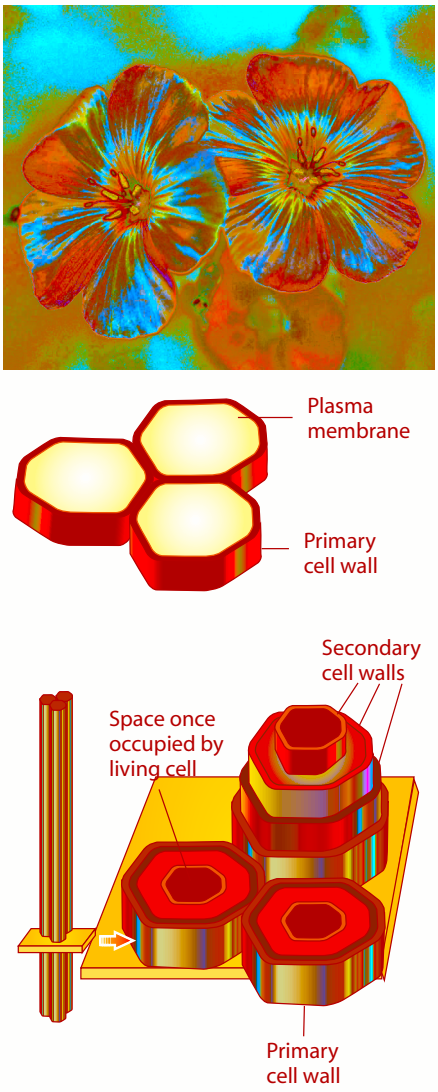
7.6 Outside the Cell

Cell Walls

To complete our tour of the cell, let's have a look at some external cell structures. Cell walls surround the plasma membranes of the cells of some bacteria and protists, many fungi and all plants. Cell walls are composed of polysaccharides (complex carbohydrates) made inside the cells and secreted through the plasma membrane, giving cells protection and support. In plants, sticky substances in cell walls also bond cells to their neighbors. One of these substances, **pectin**, is used commercially to give fruit jellies and jams their familiar consistency. Plant cell walls are made mostly of cellulose, but are further strengthened by the polysaccharide **lignin**. Tiny openings in the cell walls facilitate direct

Figure 7.36

A plant cell is surrounded by a cellulose wall outside the plasma membrane.



connections between adjacent plant cells, allowing the sharing of nutrients and other materials. (see Figure 7.36) Many fungi have cell walls made of the polysaccharide chitin, which is structurally similar to cellulose.

Plasma membranes of prokaryotes are very similar to those of eukaryotes, consisting of phospholipid bilayers punctuated by a variety of proteins. Most bacteria are also surrounded by a cell wall made of polysaccharides. However, these polysaccharides are unique to the bacterial kingdoms. Bacterial cell walls are made of the polysaccharide **peptidoglycan**, long chains of modified sugars. Short polypeptide molecules form cross-links connecting the chains to one another. As in plant and fungal cells, the cell wall of a bacterium defines the shape of the cell and reinforces the plasma membrane. For example, if the cell is in a hypotonic environment, the cell wall prevents the membrane from bursting as the result of increasing internal water pressure.

Some bacteria have a second plasma membrane outside the cell wall. This structural difference is the molecular basis distinguishing **gram-positive** from **gram-negative** bacteria. Gram stain, a violet iodine dye, is readily taken up by the thick peptidoglycan cell walls of some bacteria, called gram-positive because they turn violet with staining. Bacteria with the additional lipid bilayer fail to take up the violet dye and are called gram-negative. But these cells retain a second red dye in their outer membranes. (see Figure 7.37) In general, gram-negative bacteria tend to be pathogens, while gram-positive species are not. Gram-negative bacteria resist some of our bodies' natural defenses, as well as resisting many antibiotics, both of which attack cross-links in the bacterial cell walls. When a second membrane covers cell walls, bacterial cells receive an extra layer of protection.

Extracellular Matrix

Animal cells do not produce cell walls, but most produce supportive materials called **extracellular matrix** (ECM). As with cell walls, ECM is produced inside the cell and secreted across the plasma membrane. ECM is made mostly of glycoproteins, molecular combinations of proteins and carbohydrates. (see Figure 7.38) The most common of these is **collagen**, a word you might know if you've read labels of skin lotions or creams. Collagen is strong fibrous material and one of the molecules holding together the human integumentary system—the skin and underlying connective tissues. Collagen is widespread in the animal kingdom. It is even found in sponges, which are considered to be the most primitive animals. Some proteins of the ECM attach to integral proteins in the plasma membrane, which are in turn attached to elements of the cytoskeleton. The high degree of connectivity of ECM and other proteins helps explain the overall strength and toughness of some animal tissues. Perhaps the most familiar examples are leather, gut and sinew, still often preferred for many practical applications over synthetic versions of these materials. (see Figure 7.39)

Many types of connective tissues in your own body provide other examples of extensive ECM. All connective tissue is characterized by its organization, consisting of cells scattered throughout an extracellular

Figure 7.37

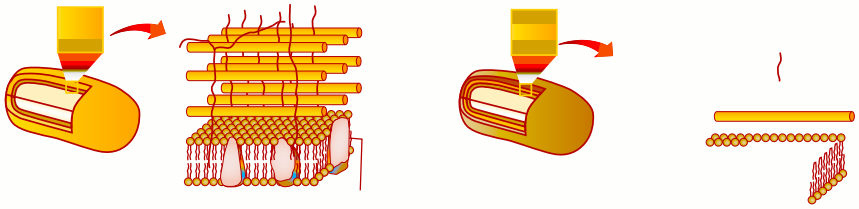


Figure 7.38

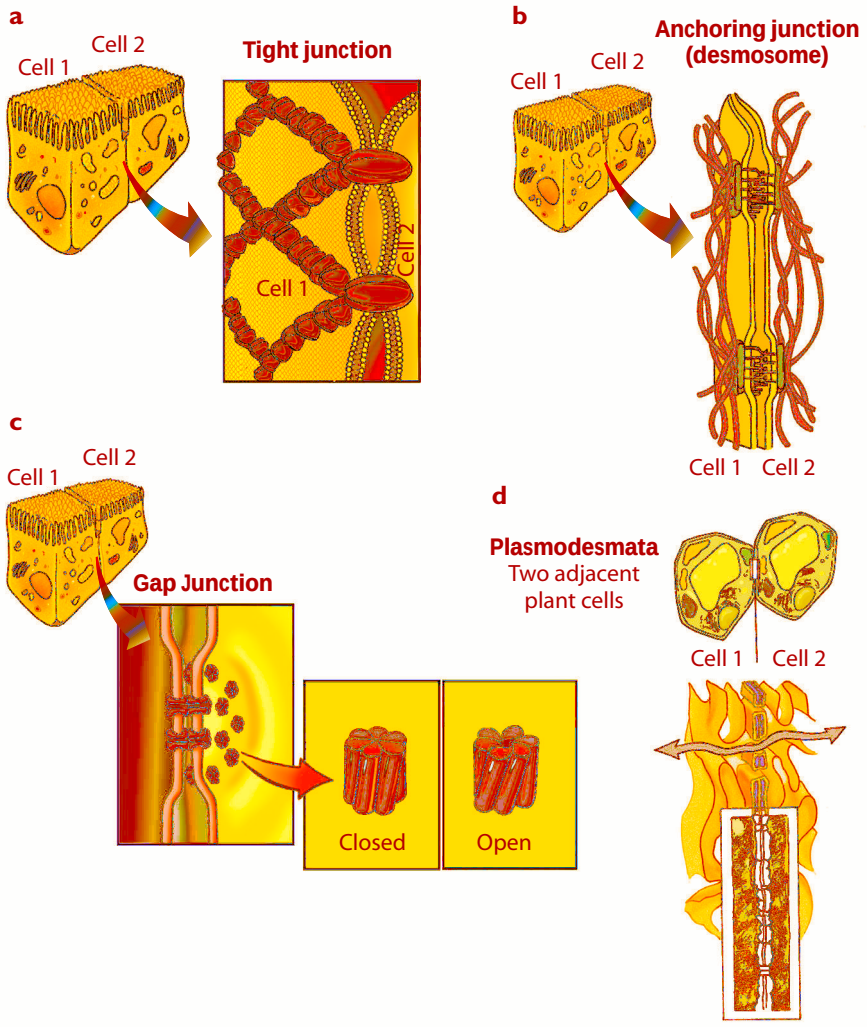
matrix. Cartilage is the connective tissue found in your nose and ears, strong enough to form distinct shapes, yet flexible enough to be bent and twisted and return to its original position. Cartilage also forms slick cushions at the ends of long bones, where it helps joints move smoothly. Bone is another example of connective tissue and contains many living cells. This is why bones can heal after a fracture. In the case of bone, the ECM is a tough mineralized material, providing support for your weight and locations for muscles to attach. (see Figure 7.40)

Cell Junctions

A final group of external proteins are those forming junctions between cells. Animal tissues are as strong as they are due partly to ECM, but also because of **cell junctions**, sites of physical attachment between cells. In addition to strength, certain intercellular junctions also allow direct communication between joined cells. **Tight junctions** occur in great numbers in tissues where cells are held closely together to form watertight barriers and prevent leaking. These are found in covering tissues, called epithelium, including those lining internal organs like the digestive system and bladder. Individual tight junctions form between complementarily shaped proteins on the plasma membranes of adjacent cells. **Anchoring junctions**, officially called **desmosomes**, work to hold together two neighboring cells, using clusters of proteins that extend into the interiors and cytoskeletons of the cells. These junctions are for

Figure 7.41

Some examples of cell junctions (**a**) tight junction (**b**) anchoring junction (**c**) gap junction (**d**) plasmodesmata



structural strength, rather than waterproofing intercellular connections. The third type of connections are **gap junctions**, which form continuous channels between adjacent cells, actually joining their cytoplasm. These allow rapid communication and the passing of molecules between adjacent cells. In plant cells, where not only membranes but also cell walls must be crossed to connect cells, gap junctions are called **plasmodesmata** (plural of plasmodesma), allowing cytoplasmic connections between adjacent cells through pits in the cell walls. Diagrams of all these cellular junctions are shown in Figure 7.41.

Even a thorough inventory and description of a cell's molecules and organelles falls short of describing "life." Describing the coordinated activities of organelles or the breakdown of molecules to release energy or

the process of cell division is just to talk about life. We can describe life's properties, but a simple definition is difficult. The cell is a classroom and laboratory for applying scientific principles to the study of life. Relationships of structure and function can be seen in many cell features and processes. Another key scientific concept, causality, applies to the interactions of molecules passing between cells to trigger changes in entire organisms, organisms as massive as a whale, as small as a worm or as tiny as a single cell. An organism might be described and mapped to its last molecule, but it remains more than the description. The organism is alive. If science will ever truly understand "life," the doorway appears to be through understanding the cell.

7.6 Check Up

1. Analyze the structural differences of plant, fungal and bacterial cell walls.
2. Compare the structural differences between gram-positive and gram-negative bacteria and explain why gram-negative bacteria tend to be pathogens.
3. Summarize the functions of the extracellular matrix in animal cells and list at least three examples.
4. Describe the various cell junctions (tight junctions, anchoring junctions, gap junctions and plasmodesmata) and give examples of where each may be found.

Chapter 7 Review

Vocabulary

Review and define the following. Terms are in the order they appear in the text.

7.1
plasma membrane
cytoplasm
genetic material
nucleus
nucleoid
cell wall
chloroplast
central vacuole
turgor pressure
mitochondrion/ mitochondria
surface to volume ratio

7.2
nuclear envelope
endoplasmic reticulum (ER)
nucleolus
crista/cristae
thylakoid
chlorophyll
rough endoplasmic reticulum (RER)
vesicle
Golgi body
smooth endoplasmic reticulum (SER)
lysosome
food vacuole
peroxisome

7.3
integral protein
peripheral protein
fluid mosaic model
transport protein
marker protein
glycoprotein
receptor protein

7.4
selectively permeable
diffusion
concentration gradient
passive transport
osmosis
hypertonic
hypotonic
isotonic
facilitated diffusion
active transport
membrane pump
pinocytosis
receptor-mediated endocytosis
phagocytosis
exocytosis

7.5
cytoskeleton
filament
microtubule
motor protein
9+2 structure
basal apparatus

7.6
pectin
lignin
peptidoglycan
gram-positive
gram-negative
extracellular matrix (ECM)
collagen
cell junction
tight junction
anchoring junction
desmosome
gap junction
plasmodesma/ plasmodesmata

Content Review

Multiple Choice

1. Paul has been observing the internal features of a cell with the use of a transmission electron microscope (TEM), but he isn't sure if he is looking at a prokaryote or a eukaryote. Which observation would indicate Paul is observing a prokaryotic cell?
a. The cell has a rigid cell wall.
b. The cell possesses chloroplasts for photosynthesis.
c. The cell has a flagellum.
d. The cell is very small and lacks a distinct nucleus.

2. Which of the following cell shapes generally has the least amount of cell surface area in relation to volume?
a. a spherical-shaped cell
b. a flattened cell
c. a noodle-shaped cell
d. an ovoid-shaped cell

3. Vesicles leaving a Golgi body are likely on their way to the
a. plasma membrane.
b. mitochondria.
c. nuclear envelope.
d. ribosome.

4. Organelles
a. are typical of prokaryotic cells, but not eukaryotic.
b. use glycoprotein membranes rather than phospholipid membranes.
c. separate chemical reactions from the rest of the cell.
d. show a 9+2 structural arrangement.

5. In the plasma membrane, the ____ of the phospholipids are sandwiched in between the ____.
a. polar, hydrophilic heads … nonpolar, hydrophobic tails
b. nonpolar, hydrophobic tails … polar, hydrophilic heads
c. nonpolar, hydrophobic heads … polar, hydrophilic tails
d. polar, hydrophilic tails … nonpolar, hydrophobic heads

6. Sodium ions (Na^+) cannot cross the cell membrane without the aid of a transport protein because sodium ions
a. are much too large to pass through the selectively permeable plasma membrane.
b. are dissolved in water and water cannot passively cross the plasma membrane.
c. cannot cross the polar, hydrophilic head of the phospholipid.
d. are charged and cannot easily cross the nonpolar, hydrophobic tail region of the phospholipid.

7. Energy is required for
a. diffusion.
b. osmosis.
c. active transport.
d. facilitated diffusion.

8. Which of the following is responsible for cell shape, strength and movement?
a. flagella
b. the cytoskeleton
c. the basal apparatus
d. cilia

9. Cell walls are found in each of the following kingdoms *except*
a. Eubacteria.
b. Fungi.
c. Plantae.
d. Animalia.

Short Answer

1. A biology student carefully listens to the lecture being presented in class regarding plant and animal cells and hears his teacher proclaim plant cells have chloroplasts while animal cells have mitochondria for their energy needs. Why should the student ask his teacher to clarify this comment? What should his teacher have said to be more accurate in his lecture?

2. Kyle and Jennifer are arguing about the size of cells in whales and humans. Kyle insists whales have much larger cells than humans, but Jennifer claims they possess cells of approximately the same size. Explain which argument is correct and point out the flaw in the incorrect argument.

3. Examine the fluid mosaic model of plasma membranes. What makes the membrane fluid? What makes the plasma membrane a mosaic?

4. Eukaryotic cells are often described as being compartmentalized. Explain cell compartmentalization and why it is more efficient than not being compartmentalized.

5. Create a table defining the various parts and organelles of cells and their general location. Include all of the following cell features in your table: cell wall, chloroplast, cytoskeleton, flagella, genetic material, Golgi body, lysosome, mitochondria, nuclear membrane, nucleoid, nucleolus, nucleus, peroxisome, plasma membrane, ribosome, rough endoplasmic reticulum, smooth endoplasmic reticulum and 9+2 cilia. Indicate whether each cell feature is possessed by prokaryotes, eukaryotes or both.

Going Further

1. **Make a Concept Map** Create a concept map to show how cells move substances across their cell membranes. Be sure to include the following terms in your concept map: active transport, concentration gradient, diffusion, endocytosis, equilibrium, exocytosis, facilitated diffusion, hypertonic solution, hypotonic solution, isotonic solution, membrane pumps, osmosis, passive transport, phagocytosis, pinocytosis, plasma membrane, protein channels, receptor-mediated endocytosis, receptor proteins and selectively permeable. Include as many additional terms as you need to complete your concept map.
2. **Make a Journal Entry** Imagine you are a physician and have been shrunken and injected into a eukaryotic cell. You have with you a medical student who is learning cell biology for her medical degree. In your journal or notebook, record your observations as you take her on a microscopic tour of the cell by explaining the various organelles and their general functions.
3. **Design an Experiment** Design an experiment to test the effects of hypertonic and hypotonic solutions on bean seedlings. Be sure to include a hypothesis, a list of materials, an experimental control and the methods by which you will assess the effects of the solutions.
4. **Investigate on Your Own** Stem cells have become a popular topic of discussion recently, as medical advances due to their use appear to be just on the horizon. Using resources from newspapers, magazines, science journals and the Internet, investigate what stem cells are and the anticipated use of these "magic cells" in future research. What is the controversy regarding stem cell research? Summarize the arguments presented by both sides of this very political debate.
5. **Speculate** Speculate what would happen to the plasma membrane and the membranes of the various organelles if the water content of a cell froze. Explain your reasoning. What overall effect would this have on the chemical reactions of the cell, even if it were allowed to thaw?
6. **Evolution** Interpret how the 9+2 cytoskeletal protein arrangement of eukaryotes supports the theory of evolution at the cellular level.
7. **Reductionism** Summarize how cytology, the study of cells, is a grand exercise in reductionism. Is reductionism necessary in order to understand cells and life processes? Explain your reasoning.
8. **Structure and Function** Describe how the marker proteins of ABO blood groups are an excellent example of structure and function at the cellular level. Why is the recognition of such markers important to the field of medicine?