

CHAPTER 2

THE CELL

INTRODUCTION ●

You and I began life as single cells. Now, both of us are composed of several trillion cells. If and when one of us conceives a child, one of these trillion cells, either a sperm or an egg, will join with one of the trillion cells, again a sperm or an egg, of our partner. This cell, now a fertilized egg, will divide into two cells, these two into four, and so on, until another trillion-celled organism develops. This organism, our offspring, will contribute a single cell to a union with his or her partner's single cell. This fertilized egg divides, and the next trillion-celled organism is our grandchild.

Cells beget cells, which beget cells. Cells have always begotten cells, ever since the first viable cells capable of begetting cells developed on our planet several billion years ago. Looking backwards, you and I began as single fertilized eggs that were the union of two single cells, each coming from the trillion-celled organisms that were our parents. Each of our parents began as a single cell formed from a sperm and an egg from our grandparents. And so on, and so on. The trillions of cells that are you and the trillions that are me are the result of a chain of cellular transmission unbroken over billions of years. You and I share great-great-great-to-a-very-high-power grandparents in some long-lost primordial soup. We have also shared grandparents

continuously on the way. Sixty million years ago, we had a grandfather who was one of the first mammals, and shortly thereafter, a grandmother who was the direct ancestor of the first primates. Possibly as recently as 200,000 years ago, our grandfather and grandmother gazed at a sunset on the African savanna and spoke about their love for each other.

Because cells beget cells, not only are you and I related, but we are also cousins to chimpanzees, orangutans, cows, snakes, frogs, mosquitoes, and oak trees. Why? Because we all share DNA, because DNA instructs a cell on how to make another cell, and because cells beget cells. To understand genetics, we must first understand the cell.

● CELL STRUCTURE

Although cells can have quite complicated structures, certain features common to all cells are important for understanding genetics. A schematic of such a cell is given in Figure 2.1.¹

The first—and very important—structure in the cell is the cell wall, referred to in “biologalese” as the *plasma membrane*. It is very much incorrect to think of the cell wall as merely a physical structure to keep the insides from spilling out, much as a sealed plastic bag might contain a cup of clam chowder. The cell wall has dynamic properties in addition to its structural properties. Embedded in the cell wall is a wide range of molecules called *receptors*. Receptors on the cell surface act as sentinels, permitting some substances to enter the cell, refusing entry to others, and signaling to the inside of the cell that something is knocking at the gate. Likewise, receptors regulate which substances inside the cell can exit the cell.

The nucleus is much like a cell within a cell, having its own “wall.” The most important structures within the nucleus are the *chromosomes*. These are packages of DNA and other molecules. They are the physical structures for genetic information and for transmitting that genetic information when the cell divides.

The material outside the nucleus is termed the *cytoplasm*. Of the various structures in the cytoplasm, three are important here. The first of these is the *endoplasmic reticulum*. This is a series of convoluted, wall-like structures connected like a large network snaking throughout the cytoplasm. The endoplasmic reticulum is less noteworthy in its own right than it is for being the location of the second important cytoplasmic structure, the *ribosome*.

A ribosome is a protein factory. Think of a ribosome as a building that contains all the tools and some of the raw materials for making proteins but lacks a blueprint. Without instructions, such a structure is incapable of manufacturing a protein. It is the DNA that provides the blueprint to a ribosome. After the blueprint is provided, the ribosome can manufacture a

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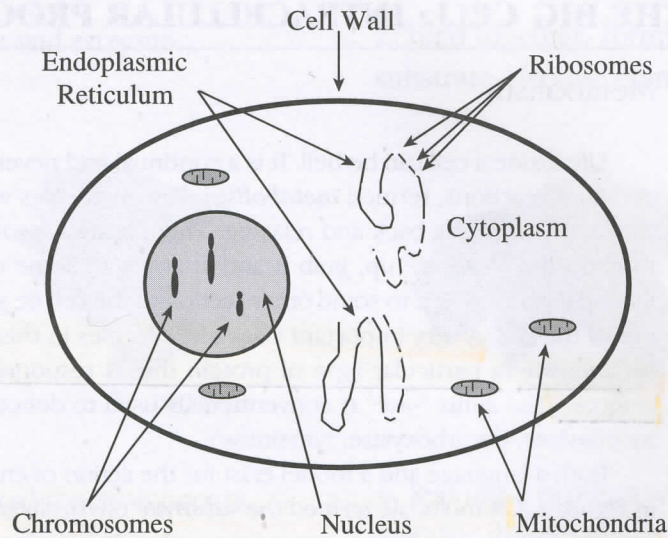


Figure 2.1 A Schematic Diagram of the Cell.

protein. There are thousands of ribosomes in the cytoplasm, so there are literally thousands of protein factories in each cell.

The third cytoplasmic structure is the mitochondrion (plural = mitochondria). Mitochondria are little energy packets that help the cell to convert chemicals efficiently.² Of equal importance is the fact that mitochondria contain DNA. This mitochondrial DNA is abbreviated as mtDNA and is minuscule compared to the amount of DNA in the nucleus. Mitochondrial DNA is maternally transmitted via the egg; sperm have mitochondria in their tails but not in their nucleus. Consequently, all siblings in a family receive their mitochondrial DNA from their mother. The fact of maternal transmission for mtDNA makes it an excellent system with which to study evolutionary trees.

Before leaving cell structure, we note an interesting hypothesis about the origin of mitochondria. It is speculated that billions of years ago, the ancestors of mitochondria were their own individual life-forms that had a leg up on most other single-celled organisms because of their efficient metabolism. The other, much larger organisms would tend to engulf and then feed on the smaller mitochondria. During evolution, some of these large unicellular organisms began to devour the ancient mitochondria. Instead of digesting the primitive grandparents of mitochondria, the large cells evolved to enslave them. The mitochondria then provided their host with efficient metabolism while the host saved the mitochondria from being eaten to extinction. If this hypothesis is true, then all of us modern life-forms owe our existence to an ancient form of slavery.³

● LIFE IN THE BIG CELL: INTRACELLULAR PROCESSES

Metabolism

Life inside a cell can be hell. It is a continual and never-ending process of chemical reactions, termed *metabolism*. Few molecules within the cell have the luxury of sitting back and relaxing. There is always some chemical ready to chop the molecule up, grab it and attach it to some other molecule, or kidnap it by moving it to some other section of the cell or, sometimes, entirely out of the cell. A very important class of molecules in this turbulent scene is the *enzyme*, a particular type of protein that is responsible for a chemical reaction. The suffix “-ase” is conventionally used to denote an enzyme (e.g., hydroxylase, decarboxylase, tyrosinase).

Both a language and a model exist for the action of enzymes, as depicted in Figure 2.2. A molecule termed the *substrate* physically binds with a specific enzyme, forming a substrate-enzyme complex. The analogy of a lock and key is used to describe this process. Not every substrate can bind to a particular enzyme, and not every enzyme can bind to a specific substrate. The substrate and enzyme must physically fit together, in the same way that a particular key opens a specific lock. Thus, one encounters such lingo as “binding site” to refer to that portion of the enzyme that the substrate recognizes and binds to.

Once a substrate-enzyme complex is formed, a chemical reaction occurs. For example, a hydrogen atom might get lopped off of the substrate, or a hydroxyl group (a combination of hydrogen and oxygen atoms) may be added. The altered substrate is now called a *product*. The product and the enzyme dissociate. The enzyme goes its merry way, hoping to encounter another substrate molecule to mutilate, and the product usually becomes the substrate for a different enzyme. In this way, a chain of chemical reactions occurs until something of importance is made. This chain of reactions is called a *metabolic pathway*.

Figure 2.3 illustrates the metabolic pathway in the synthesis of norepinephrine, an important *neurotransmitter* (a chemical that communicates between nerve cells). The process begins with a molecule called tyrosine that acts as a substrate for the enzyme tyrosine hydroxylase. Tyrosine binds to tyrosine hydroxylase that converts it into the product dihydroxyphenylalanine, better known as DOPA. DOPA is then converted into dopamine (DA) by the action of the enzyme DOPA decarboxylase. At this point, one of two things can happen to dopamine, depending on the type of nerve cell in which the metabolic path is operating. In some nerve cells, no further chemical conversions will take place, and the DA will be used as a neurotransmitter. In other cells, the enzyme dopamine β -hydroxylase converts dopamine into norepinephrine (NE), which will be used as the neurotransmitter.

We can now begin to glimpse the important role of genes in this process. DNA contains the blueprint for proteins, and enzymes are a particular class

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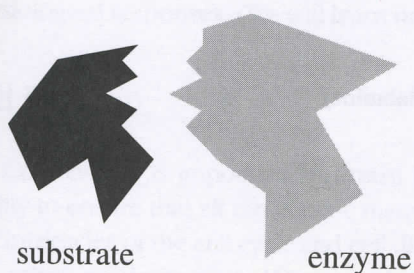
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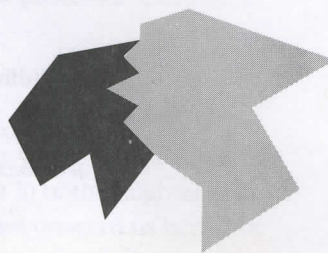
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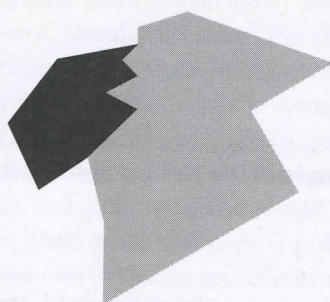
1. Substrate and enzyme...



2. bind together, forming a substrate-enzyme complex.



3. A chemical reaction occurs...



4. leaving a product when the enzyme dissociates.

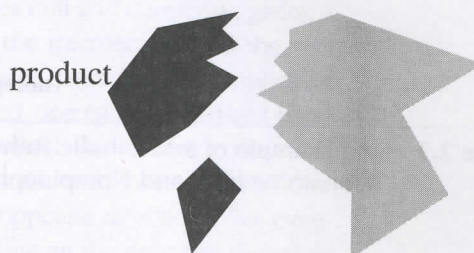


Figure 2.2 A Model for Enzyme Action.

of proteins. Consequently, DNA has the instructions for the enzymes that are responsible for the chemical reactions in hundreds of metabolic pathways occurring in each one of our cells.

Transportation

DNA contains the blueprint for making a protein or an enzyme. The actual manufacture of the protein, however, takes place at a ribosome that could be on the endoplasmic reticulum almost anywhere in the cell. Many proteins, however, have to be at a specific place in the cell in order to perform their appropriate cellular duties. It is very inefficient—although it occurs at times—for the protein to be left alone to bang into this molecule and collide with that substance until, by dumb luck, it gets to where it belongs. More often, mechanisms and structures exist within the cell to transport the protein to its appropriate location.

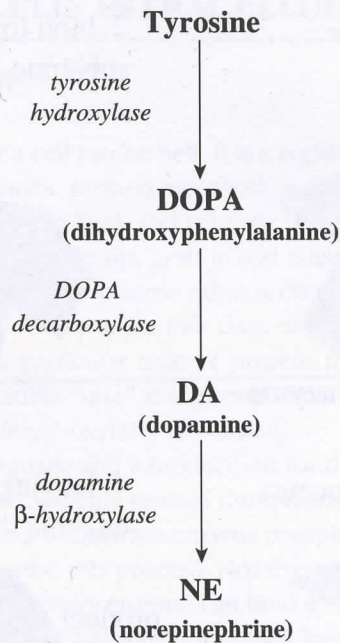


Figure 2.3 An Example of a Metabolic Pathway: Synthesis of the Neurotransmitters Dopamine (DA) and Norepinephrine (NE).

Transportation is not limited only to proteins and enzymes. Many other substances, especially the end products of a metabolic path, are actively transported.

Storage

Much as you and I might have a special location in the refrigerator for the butter dish, many cells have storage units for certain molecules. These storage units, called *vesicles*, usually serve two purposes. First, vesicles can store large amounts of a molecule in a strategic location so that these molecules can be released en masse at a critical time. Second, storage in vesicles can prevent the molecules from being *degraded*—a fancy term for maiming and mutilation by roving gangs of psychopathic enzymes.

For example, consider the molecule CRH (corticotropin releasing hormone). It is manufactured in the cells of a particular area of the hypothalamus (a structure in our brains) called the paraventricular nucleus. Newly made CRH is transported to a vesicle in these cells until the number of vesicles and amount of CRH are large enough to inhibit the manufacture of new CRH. Within the vesicle, a molecule of CRH has a happy and placid existence, relaxing with its neighboring CRH molecules—that is, until something dreadful

occurs. If a person experiences fear, the nerves in the brain containing cells fire a stream, which carries out a physiological response.

Cell Division

Cell division is a process of great fidelity to ensure the continuity of life. The intricacies of this process are two terms are important: *mitosis* occurs for all of our cells, and *meiosis* occurs for all of our sex cells. Chromosomes duplicate (called sister chromatids) and then separate at the *centromere*. During *meiosis*, characteristic X-like structures called tetrads are formed, separating the nuclear material into four series of steps, two of which are on the left-hand side of the chromosome and pull the chromosomes and pull them in opposite direction while its sister chromatid eventually gives two chromosomes on the left of the centromere and a centromere. When this process is complete, the cell has four chromosomes.

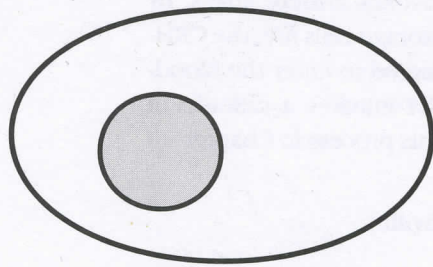
The second major type of cell division is *meiosis*, the specialized process that produces sex cells (Figure 2.5). Obviously, sex cells are different from other cells—if it were, the process of *meiosis* begins with a single cell that takes place in order to produce four cells. There is a physical separation of the material into two parts from the mother and the father, called *recombination* or *crossing over*, and the paternal and maternal information about the cell is important to recognize the difference between one another—the paternal and maternal chromosomes signify that the two already will have a different set of chromosomes contains one or more chromosomes.

occurs. If a person encounters something that provokes anxiety, stress, or fear, the nerves in the brain that lie next to the CRH storage cells fire, the CRH-containing cells fire in response, and the CRH is released to enter the bloodstream, which carries it to other cells. There, CRH initiates a cascade of physiological responses. (We will learn more about this process in Chapter 4.)

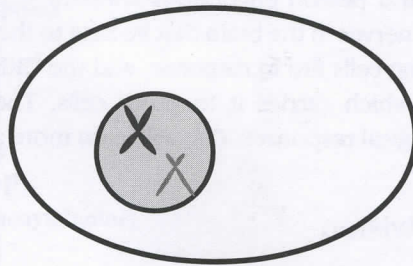
Cell Division

Cell division is important and must be carried on with a high degree of fidelity to ensure that all the genetic material is present in both daughter cells. The intricacies of the cell cycle and cell division need not concern us here, but two terms are important. *Mitosis* is the ordinary form of cell division that occurs for all of our cells, save sperm and egg. It is depicted in Figure 2.4. The chromosomes duplicate, each one making an exact replica of itself, and the two copies (called sister chromatids) are joined together in a region called the *centromere*. During this stage, the chromosomes coil and condense, giving a characteristic X-like shape that is visible under the microscope, and the wall separating the nucleus from the cytoplasm begins to degrade. In a complicated series of steps, two sets of spindles are constructed, one each on the right-hand and left-hand sides of the cell. The spindles then attach themselves to the chromosomes and pull apart the joined chromosomes, with one pulled in one direction while its carbon copy is pulled in the opposite direction. This eventually gives two complete sets of chromosomes, one on the right and the other on the left of the cell. Nuclear membranes form around the two sets of chromosomes and a cell wall is constructed down the middle of the cytoplasm. When this process is completed, there are now two cells.

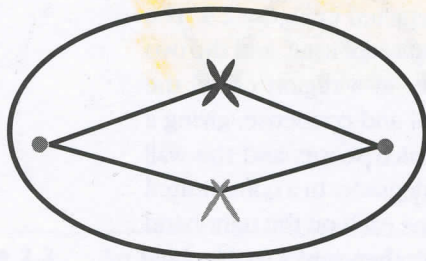
The second major type of cell division is *meiosis* (the adjectival form is *meiotic*), the specialized cell division that produces sperm and eggs (see Figure 2.5). Obviously, ordinary mitosis cannot be used for these important cells—if it were, the number of chromosomes would double each generation. Meiosis begins with the replication and condensing of the chromosomes that takes place in ordinary cell division. But then an important difference occurs: There is a physical pairing of the chromosome from the father with its counterpart from the mother. At this point, a very important phenomenon, termed *recombination* or *crossing over*, often occurs. In recombination, the maternal and the paternal chromosomes exchange DNA with each other. More information about recombination is given in Chapter 10. For now, it is important to recognize that there are four strands of DNA physically connected to one another—the “maternal” chromosome and its “carbon copy” and the “paternal” chromosome and its “carbon copy.” (I use quotation marks here to signify that the terms “maternal” and “paternal” are used loosely, because the two already will have exchanged DNA. Hence, the “maternal” chromosome contains one or more sections of the original paternal chromosome and the



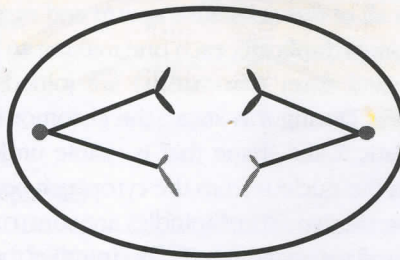
I. Chromosomes are expanded into long structures in the nucleus and are invisible under the light microscope.



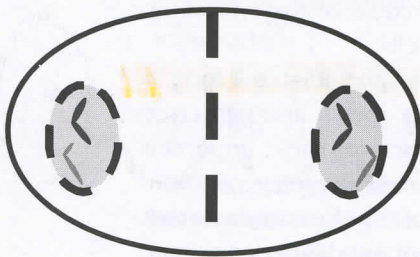
II. Chromosomes replicate and condense. With appropriate staining, they can now be seen under a microscope.



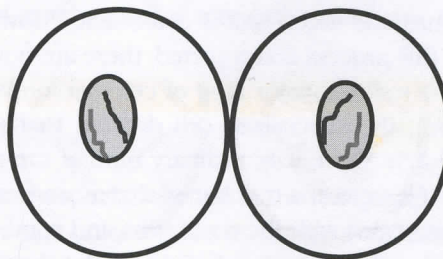
III. The nuclear wall degrades, spindles form and attach themselves to the chromosomes.



IV. Spindles pull the chromosome pairs apart, pulling them to opposite poles of the cell.



V. Nucleus develops around each set of chromosomes and the cell wall starts to form, splitting the cell into two parts.



VI. Nucleus and cell wall complete development and chromosomes expand, giving two daughter cells.

Figure 2.4 Mitosis, the Process of Cell Division in All Cells Except Sperm and Egg.

Figure 2.5



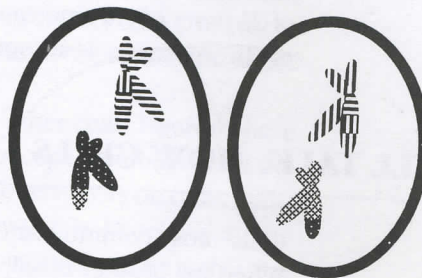
I. As in mitosis, chromosomes replicate and condense.



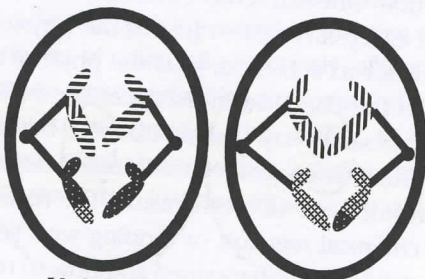
II. Unlike mitosis, the maternal (solid) and paternal (dotted) chromosomes pair up and exchange genetic material.



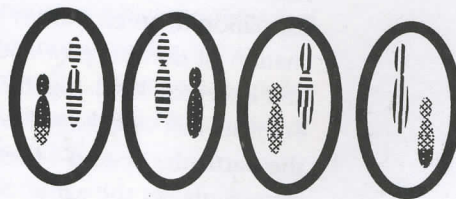
III. Spindles form, attach themselves, and pull the chromosomes to the poles of the cell.



IV. The cell divides.



V. Spindles form again and pull each chromosome away from its partner.

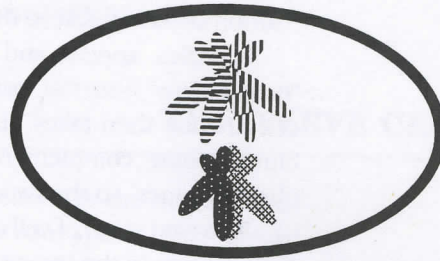


VI. Each cell divides again, reducing the number of chromosomes to half that of the original cell.

Figure 2.5 Meiosis, Cell Division That Generates a Sperm or an Egg.



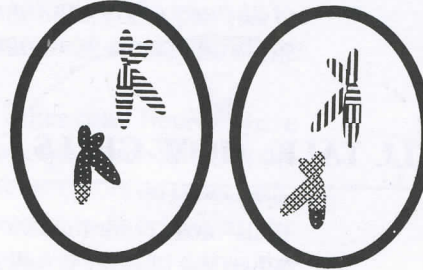
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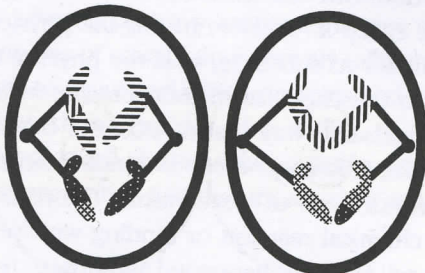
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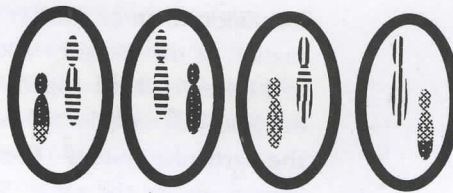
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VI. Each cell divides again, reducing the number of chromosomes to half that of the original cell.

Figure 2.5 Meiosis, Cell Division That Generates a Sperm or an Egg.

"paternal" chromosome contains maternal DNA. The same applies to the "carbon copies" because they too will have exchanged genetic material.)

Spindles appear and separate the "maternal" chromosome and its "carbon copy" from the "paternal" chromosome and its "carbon copy." Ordinary cell division then takes place, generating two cells each with the complete chromosome complement. That is, each of us humans has 23 pairs of chromosomes, so the two cells will also have 23 pairs of chromosomes.

The next stage of cell division is called *reduction division*, and it is essentially mitosis in the two pre-germ cells. Here, spindles appear just as they do in mitosis and attach themselves to the chromosomes and their "carbon copies." The spindles then pull the chromosomes into the two poles of the cell and the cell divides. Now each cell will contain 23 chromosomes instead of 23 *pairs* of chromosomes. Hence, the necessary reduction in the number of chromosomes is accomplished.

● CELL TALK: HOW CELLS COMMUNICATE

Cells must communicate—and not merely to their immediate neighbors. When my bladder is full, the appropriate cells in my lower gut must get the message to my eyeballs to look around for a restroom. By far the most frequently used mechanism for cell talk is chemical communication.

The mechanism for chemical communication is analogous to the binding lock and key model of enzyme action. One cell sends out a chemical message. Another cell contains a molecule called a *receptor*. Just as the physical conformation of an enzyme is specific for its substrate, so is the physical conformation of the receptor specific to the chemical messenger. The messenger and receptor bind together in the same way that a substrate binds to an enzyme. Just what happens after the messenger-receptor binding depends on the particular system—there is a wide array of mechanisms. The result, however, is always the same. Some chemical reaction or binding with yet other molecules occurs, informing the cell what has happened and how to respond.

Receptors can reside on the cell wall, in which case they are called cell *surface* or *membrane receptors*, or within the cytoplasm and the nucleus of the cell (*intracellular receptors*). All receptors are proteins or have a protein somewhere within their structure.

Cell talk can happen between very different types of cells quite far away from each other. The chemical communicators in this case are called *hormones*. For example, certain cells in the pituitary gland, located just underneath the brain, send a messenger hormone called ACTH to cells in the adrenal gland, located on the top of the kidney. The mode for this type of distance communication is to send the message through the blood.

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Another type of cell talk occurs between nerve cells. Let us first explore the anatomy of nerve cells and then discuss how they talk to one another.

THE NERVE CELL •

One of the most important types of cells for behavior is the nerve cell or *neuron*. Popular similes and metaphors for the nervous system often invoke electricity and electrical engineering. A psychotic person may be described as having a short circuit in the brain, but who ever refers to an incontinent person as having a short-circuited kidney? It is indeed true that nerve cells generate electrical impulses, but it is equally true that they, just like all other cells, are organized bundles of chemical reactions. Furthermore, genes play just as important a role in the chemical reactions of the nerve cell as they do in the kidney cell.

Nerve cells have the same logical structure as other cells. Neurons have a cell wall, and a host of chemical sentinels and gatekeepers embedded in the plasma membrane perform the same function as the receptors on other cells. They announce to the neuron that some messenger is knocking at the gate, let other messengers in, keep certain ones out, and see to it that the appropriate molecules inside the neuron either stay inside or exit the neuron as needed. Neurons have mitochondria, an endoplasmic reticulum, and thousands of ribosomes busily making proteins and enzymes from the DNA blueprint. Also just like other cells, neurons have a nucleus with chromosomes. Like the DNA in your bone marrow, muscles, skin, and lungs, the DNA in the nerves of your brain is actively telling your neurons which proteins and enzymes to make and which proteins and enzymes not to make.

What then, besides the ability to generate an electrical impulse (i.e., *depolarize*) distinguishes a nerve cell from other cells? The answer is nothing, really. It is just that most nerve cells look funny.

The Neuron

Although neurons come in all shapes and sizes, the typical neuron, depicted in Figure 2.6, resembles a regular ellipsoid cell, looking like something extruded from a pasta machine that was having a bad day. Suppose that you intend to make vermicelli. Instead of a long, very thin cylinder, the pasta dough starts coming out as a frizzled mess, followed by the desired structure for a strand of spaghetti, but ending with a big irregular blob with frizzy ends. That is a neuron. It looks like an octopus with a neck the size of a giraffe.