Chapter 2

The Cell

You and I began life as single cells. Now, both of us are composed of several trillion cells. 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/her partner’s single cell. This fertilized egg divides, and the next trillion-celled organism is our grandchild.

Cells beget cells beget cells. And 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 are our parents. Each of our parents began as a single cell formed from the sperm and eggs of 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 led to 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.


2.1 Structures in the cell

Although cells can have quite complicated structures, there are certain features common to all cells that are important for understanding genetics. A schematic of such a cell is given in Figure X.X. To understand the cell, think of a medieval castle.

2.1.1 Plasma membrane and receptors

The first—and very important—structure in the cell is the cell wall, referred to in “biologicalese” as the cell or plasma membrane. It is very incorrect to think of the plasma membrane as only a physical structure designed to keep the insides from spilling out, much as a sealed plastic bag contains a cup of clam chowder. The cell membrane has dynamic properties in addition to its structural properties. Embedded in the membrane is a wide range of molecules collectively called receptors.

Following the castle analogy, receptors on the cell surface have two functions: sentinels and gatekeepers. In a castle, sentinels patrol the wall and then convey messages from those approaching the castle to the occupants inside. In the cell, sentinels convey messages but they are chemical messages. Unlike the castle
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where a single sentinel can convey a wide variety of messages, there are a wide
variety of chemical sentinels and each usually conveys one and only one message.

The role of a gatekeeper in a castle is to regulate who can and cannot enter
and leave the structure. Gatekeeper receptors do the same for the cell. Like
the sentinel receptors, chemical gatekeepers are not generalists. Instead there
are many different types of gates and gatekeepers, each one specific to a certain
chemical or class of chemicals.

2.1.2 The nucleus

Most medieval castles contain a castle keep. The keep is a castle within a castle
that functions as residence of the royal family and also the last line of defense
against marauders. The nucleus is the cell’s castle keep. It is akin to a cell
within a cell that has its own membrane.

The members of the royal family are the chromosomes. Each chromosome
is a long strand of deoxyribonucleic acid (DNA) packaged in a complicated way
around proteins. Unlike feudal royalty, there is no hierarchy of authority within
the chromosomes. Each one acts on its own with full authority.

Also, the chromosomes lack the freedom of royalty. In fact, their are more
akin to slaves than to rulers. They are effectively imprisoned within the nu-
cleus. True, they do issue edicts in the form of chemical instructions, but the
instructions are largely a mechanical response to the messages received from the
sentinels (receptors) and the substances entering the cell.

2.1.3 Vesicles

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
are called vesicles and they usually serve two purposes. First, vesicles can store
large amounts of a molecule in a strategic location so that they can be released
en mass 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).
This 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 is 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 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 that carries
it to other cells. There, CRH initiates a cascade of physiological responses. (We
will learn more about this process in Chapter X.X).
2.1.4 Other important structures

Just as a castle contains many specialized structures (e.g., a livery, smith, baker), the cell has numerous organelles—structures that perform specific functions for the cell. It is not important for our purposes to know all of them, but some of them will recur throughout this book, so they deserve mention here.

Snaking throughout the cell, usually in close proximity to the nucleus is the endoplasmic reticulum, a pedantic Latin term meaning “network within the plasma.” This network is less important in its own right than for the structures that tend to congregate on it—the ribosomes. A ribosome is a protein factory. Think of the 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. The blueprint used by the ribosomes is a chemical message sent from a section of the chromosome within the nucleus. Ribosomes are generalists. A single ribosome can take any message and translate it. Hence, one ribosome will produce many different types of proteins.

Another important structure is the mitochondrion (plural = mitochondria). Mitochondria are little energy packets that help the cell to convert chemicals efficiently. 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. Consequently, all siblings in a family receive their mitochondrial DNA from their mother. The fact of unilateral transmission for mtDNA makes it an excellent system with which to study evolutionary trees.

There is 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.\(^1\)

Keep in mind that the presentation here is very simplified and does not reflect the complexity of life within the cell. There are many other organelles that are important for the cell but need not concern us. For example, the Golgi complex pictured in Figure 2.1 acts like a post office. It packages proteins that are then sent to other parts of the cell. There are waste disposal centers that break down molecules. The cell also has a miniature skeleton that helps to maintain structural integrity and also functions as a highway system to transport

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\(^1\)Of course, a different scenario is possible. Perhaps the mitochondria developed their own mechanism that allowed them to be engulfed, but not digested, by other species in order to escape predation. Like much evolutionary speculation, the true answer may be lost in history.
substances from one part of the cell to another.

2.2 Cell division

Cell division is important and must be carried on with a high degree of fidelity to assure 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 X.X. Normally, the chromosomes in the nucleus resemble a jumbled ball of string as depicted in Figure 2.1. When the cell is ready to divide, each chromosome replicates, making a carbon copy of itself. The two copies (called sister chromatids) are joined together in a region called the *centromere*. During this stage, the sister chromatids coil and condense into dense bodies, giving the characteristic X-like shape that is visible under the microscope.

The wall separating the nucleus from the cytoplasm begins to degrade. In a complicated series of steps, two sets of spindles are constructed, one on the right and the other on the left-hand side of the cell. The spindles then attach themselves to the chromosomes and pull apart the joined chromatids so that one is 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*) and it refers to the specialized cell division that produces sperm and eggs (see Figure X.X). Obviously, ordinary mitosis cannot be used for these important cells. Otherwise, the number of chromosomes would double each generation.

Meiosis begins with the replication and the chromosomes that takes place in ordinary cell division. But then an important difference occurs—there is a physical pairing of the chromosome that you received from your father with its counterpart that you received from your mother. At this point a very important phenomenon, termed *recombination* or *crossing over*, often occurs. In recombination, the maternal and the paternal chromosome 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.” (Quotes are used here to signify that the terms “maternal” and “paternal” are used loosely because the two will have already exchanged DNA. Hence, the “maternal” chromosome

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2 The “jumble,” however, is far from random. There is a structure to it that will be discussed in Section X.X
contains one or more sections of the original paternal chromosome and the “pa-
ternal” 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 “car-
bon copy” from the “paternal” chromosome and its “carbon copy.” Or-di-

nary cell division then takes place, generating two cells each with the
complete chromosome complement. That is, each of us humans have 23
pairs of chromosomes, so the two cells will also have 23 pairs of chromo-
somes.

The next stage of cell division is called reduction division, and it is es-
"sentially mitosis in the two pre-germ cells. Here, spindles appear just as
they do in mitosis and attach them-
selves 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 chromo-
somes instead of 23 pairs of chromo-
somes. Hence, the necessary reduc-
tion in the number of chromosomes is
accomplished.

2.3 Metabolism

Life inside a cell can be hell. It is a continual and never ending pro-
cess 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, some-
times, 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.

There are both a language and a model for the action of enzymes, depicted
here 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 as a particular key opens a specific lock.\(^3\) 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. The reaction will be either a cut or paste operation. For example, a hydrogen atom might get lopped off of the substrate (a cut operation), or a hydroxyl group (a combination of hydrogen and oxygen atoms) may be added to the substrate (a paste operation). The altered substrate is now called a *product*.

After the enzyme performs its action, the product and the enzyme dissociate. The enzyme goes its merry way hoping to encounter another substrate molecule to mutilate, while 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 dopamine and norepinephrine, two important neurotransmitters (i.e., 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-\(\beta\)-hydroxylase converts dopamine into norepinephrine (NE) which will be used as the neurotransmitter.

\(^3\)Physically, the “lock” and the “key” are three dimensional structures and the binding is determined by the electromagnetic charges of the enzyme and substrate.
We can now begin to glimpse the important role of genes in this process. DNA contains the blueprint for proteins. Enzymes are a particular class 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 and every one of our cells.

2.4 Cell talk

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 (see Section 2.1.1). Receptors can reside on the plasma membrane, in which case they are called cell surface or membrane receptors, or within the cytoplasm and the nucleus of the cell (intracellular receptors). Most receptors are proteins or have a protein embedded within their structure.

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.

Cell talk can happen between adjacent cells or between very different types of cells quite far away from each other. Nerve cells communicate using neurotransmitters, a class of molecules that send a signal from one nerve cell to its adjacent nerve cells. Hormones are a class of long distance communicators. 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. A third type of communicator class is the cytokine. These are proteins or protein complexes that our immune systems use to communicate to other cells.

2.5 The Neuron

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 an organized bundle 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 membrane, and there are a host of chemical sentinels and gatekeepers embedded in the plasma membrane that 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. And, just like other cells, neurons have a nucleus with chromosomes. Like 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.

Although neurons come in all shapes and sizes, the typical neuron, depicted in Figure 2.6, resembles a regular ellipsoid cell 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 finished off a big irregular blob with frizzy ends. That is a neuron. It looks like an octopus with a neck the size of a giraffe.

There is a very good reason for this structure and for the electrical nature of the impulse in neurons. Imagine that you mistakenly sat on an anthill, and the little critters, resenting the intrusion, declare war on your bottom. How long would it take your body to react if those assaulted cells in your gluteus maximus had to chemically communicate this fact to their neighboring cells, those cells to their own neighbors and so on, until the message finally got to your brain? Then the brain cells would have to chemically communicate the message “Ouch! Get off this stupid anthill!” back down the millions of cells, one cell at a time, until it would prompt movement of the appropriate muscles.

The speed of electrical transmission is on the order of turning on a switch and watching the bulb light up. That is why nerves use electricity. But why the funny structure? The answer is that one nerve uses chemistry, not electricity, to communicate with the next nerve. If nerves were just like other cells, there could be a million very tiny neurons between your butt and your brain. The chemical transmission between neurons would be painfully slow, even if each individual neuron fired an electrical burst. But with that very long, thin, spaghetti-like structure in Figure 2.4, only a few neurons are needed to connect your seat to your central processing unit. The chain of chemical transmission to electrical impulse to chemical transmission to electrical impulse becomes a very efficient way to send rapid messages. In the case of the anthill, electric impulses along very elongated cells permit a speedy retreat and allow you to live to sit another day.

Naturally, scientists must come up with fancier names than “spaghetti-like structure” to refer to the anatomy of the neuron. The large blob that contains the nucleus is called the cell body. The long vermicelli portion, along which the electrical impulse is carried, is termed the axon; it is sheathed in an “insulator” called myelin. There are two types of “frizzled ends” in a neuron. Those on the input side are called dendrites; they receive information from (usually) other nerve cells. At the output side, there are terminals called synaptic buttons that transmit the information to (usually) other nerve cells.

Do not imagine any of these structures, especially the dendrites and the synaptic buttons, as being like a copper wire. They are parts of cells and thus have cytoplasm, cell membranes, vesicles, proteins, enzymes, and a host of other chemical molecules. The neuron is really a chemical complex, not an electronic relay.

### 2.5.1 Neuron talk

It is important to place the chemical transmission of neurons under a microscope to examine the process in more detail. Not only will it give us a better appreciation for cell talk, but it will also help us to understand an important focus of today’s genetic research on behavior, especially for psychiatric disorders.
The process of neural cell talk is outlined in Figure 2.5. Pictured here are portions of two neurons—the one that fires (the presynaptic neuron) and the one that responds to the firing of the first one (the postsynaptic neuron). Usually, the two neurons do not physically touch each other. Instead, there is a physical gap between neurons called the synapse (a.k.a. synaptic cleft or synaptic junction). The adjectival form of this word—synaptic—is used as a suffix for a number of biological terms (e.g., presynaptic receptor—a receptor on the presynaptic neuron; postsynaptic receptor—a receptor on the postsynaptic neuron).

When the first neuron fires, vesicles containing the chemical messenger (aka neurotransmitter) move to the cell wall and release the messenger into the synapse. This process occurs very rapidly. And with a large number of vesicles and thousands of neurotransmitter molecules, release resembles a flash flood more than a trickling stream.

The physical force behind the release pushes the neurotransmitter across the synapse. Sitting on the plasma membrane of the postsynaptic neuron is a host of receptors. The neurotransmitter and receptor bind together in the same lock-and-key way that substrate and enzyme bind. The binding between
neurotransmitter and receptor sparks a chemical reaction in the postsynaptic neuron that, in turn, initiates a whole cascade of chemical events that alters the whole chemical state of the neuron. In some cases, this change of state is excitatory and makes the postsynaptic neuron more likely to fire. In other cases, the change is inhibitory and decreases the probability of firing.

The final step in the process is really an exercise in tidy housekeeping. It is important not to let the large mass of neurotransmitter stay in the synapse. Otherwise, the constant binding, unbinding, and rebinding of the neurotransmitter with the postsynaptic receptor would keep the postsynaptic neuron in a state of perpetual change. Two major mechanisms take care of the excess neurotransmitter. The first is called reuptake. Here, the neurotransmitter binds to a transporter—a specific receptor on the presynaptic neuron—gets “reabsorbed” back into the cell. The second mechanism is enzymatic degradation. One set of enzymes is lurking around the synapse, just ready to pounce on any wayward neurotransmitter. Another set lies low in the presynaptic neuron, waiting to ambush any neurotransmitter that went through the reuptake process but has not made it back to the safety of a vesicle.

2.5.2 Consequences of neuronal talk

The fact that thousands of molecules of neurotransmitters flood the synaptic cleft and bind to their receptors does not end the story of communication among neurons. A number of salient events then happen in the post-synaptic neuron. To understand this clearly, we must first realize that neurons are not connected to each other like links in a chain. Thousands of neurons connect to that single postsynaptic neuron depicted in Figure 2.4. Hence, the state of the postsynaptic neuron depends less on what happens in any single pre-synaptic neuron and more on the cacophony of events occurring in all of the pre-synaptic neurons that impinge on it.

Still, to understand the end result of a neuronal chemical message it is useful to consider the influence of one and only one pre-synaptic neuron. For didactic purposes, we can distinguish two types of effects of neurotransmitter binding—immediate, short-term influences and eventual long-term effects.

The immediate effects are the opening and closing of ion channels illustrated in Figure 2.6. The post-synaptic receptor molecule is often linked to a series of other molecules, one being a protein or enzyme that influences channels in the postsynaptic neuron that permit ions (electrically charged atoms) to enter or exit the neuron. Figure 2.6 illustrates the specific case where the binding of a neurotransmitter with its receptor changes the conformation of the receptor to permit positively charged calcium (Ca) and sodium (Na) ions to flow into the postsynaptic neuron.

In their resting state, neurons have a negative charge. A large influx of positive ions and efflux of negative ions will change the polarity of the neuron so that it “fires.” On the other hand, a large influx of negative ions and efflux of positive ions will inhibit the neuron, preventing it from firing.

For our purposes here, the long-term effects of neurotransmitter binding
Figure 2.6: Short-term effect of neurotransmission: Ion channel openings and closings.
Figure 2.7: Long-term effects of neuronal transmission: Genetic regulation.

are more important than the short-term effect although they are much less understood. An example of the favored model is illustrated in Figure 2.7. The receptor is physically connected to a series of molecules that form a scaffold. When the neurotransmitter binds with the receptor it alters the conformation of several of the proteins in the scaffold, permitting them to bind with other molecules (the complex on the right-hand side of Figure 2.7). The binding induces a cascade of chemical reactions that result in a second messenger system in the post-synaptic neuron. As opposed to the short-term effects of binding which alter the immediate electrical state of the next neuron, the long-term effects change the chemical state of the neuron.

The genetic consequence of the second messenger system is that alters what we will term DNA dimmer switches. Think of each gene in a cell as a light that is connected to a dimmer switch. For many genes in a given cell type, the switch is completely turned off. For housekeeping” genes (i.e., genes required for basic cellular functions in all types of cells), the switch is perpetually on. For many other genes, however, the switch can be turned up or down in response to the cell’s immediate needs.

The long-term effect of neurotransmission instructs the DNA machinery in the post-synaptic neuron to start making more blueprints for certain types of proteins and enzymes and fewer blueprints for other proteins and enzymes. This is a phenomenon called gene regulation or gene expression, the details of which
will be explicated in Chapter X.X. The important lesson is to recognize the lemonade quality of neuronal cell talk. Environmental stimuli that impinge on, say, your visual system initiate a whole cascade of events in your neurons that effectively turn some genes on and shut other genes down in your brain cells. The mere fact of looking at something influences the genes in your central nervous system.

### 2.5.3 Neuron talk and genes

How do genes fit into neuronal transmission? There are several different ways. In the previous discussion of metabolic pathways, we have already seen how DNA contains the blueprint for the enzymes that synthesize neurotransmitters (review Figure 2.2). The receptors for neurotransmitters, both on the firing neuron and its recipient, do not appear from anywhere. DNA contains the code for these receptor proteins and/or the enzymes that synthesize them. DNA also holds the information for making the enzymes that metabolize the extra neurotransmitter that gets released and for the transporter proteins that carry the neurotransmitter back into the presynaptic neuron.

Many steps in the second messenger system are also influenced by proteins and enzymes the blueprints for which are encoded in the DNA. Finally, the long-term result of cell talk among neurons is to “turn on” certain genes in the post-synaptic neuron and to “turn off” other genes. Not only does DNA have the blueprint for these important proteins and enzymes, but it may also play a role in the numbers of protein or enzyme molecules that are synthesized and their distribution throughout the neuron. Scientific knowledge on this is skimpy, but it is likely that genes may influence such factors as the number and size of vesicles containing neurotransmitters, the number of receptor molecules, and perhaps even the density at which these receptors cluster at various places on the neuronal wall. Much research is needed to clarify the role of DNA in the human nervous system, but there is no doubt that without DNA in each and every neuron, we humans would have no nervous system at all.

### 2.6 Three disclaimers about the nervous system

First, if it has not already been done, I hope that one day an historian of the English language will trace the evolution of the word “nervous.” The Latin word “nervus,” from which the English word derives, means a sinew, and the word was apparently taken up by anatomists to refer to the tendon-like structure of the axons of some nerves. Somehow along the way, the word developed connotations of worry and apprehension on the one hand and jitteriness and agitation on the other. This is very curious because our nervous system plays just as important a role when we are calm and relaxed as it does when we are tense and anxious.

Second, although the nervous system plays a crucial role in behavior, one should not conclude that genes influencing behavior must do so by acting directly
in the nervous system. All of us large, multicellular life forms are conglomerations of many different systems that talk to one another and can influence behavior. Later on (Section X.X), we will see how a gene for an enzyme in the liver can reduce the risk of alcoholism.

Finally, a disclaimer is needed for the simplicity with which the nervous system has been described. From a scientific view, almost every statement made above requires qualifications because the nervous system is a very, very, very complicated place where virtually every rule has its exception. For example, a few neurons do communicate electrically and not chemically, and not every neurotransmitter is synthesized from enzymes. We will soon see that with genes and their physiological effects, complexity and perplexity are the rule instead of the exception.