STEVEN FARMER

STRANGE CHEMISTRY

THE STORIES YOUR CHEMISTRY TEACHER
WOULDN'T TELL YOU

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The Stories Your Chemistry Teacher Wouldn't Tell You

Steven Farmer

Sonoma State University, Rohnert Park, California, USA

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Dedication

I would like to dedicate this book to my parents James and Margaret.

Throughout my whole life whenever I looked, you were there; ready to give me love and support, guidance and security, and praise and encouragement. You filled me with your dreams and showed me what it takes to succeed in life. Without you both none of the things I have accomplished would have been possible. I am truly blessed to have such incredible parents, and I love you both.

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Preface

Growing up in Northern California was much more curious than one might think. Napa, being part of Northern California, was affected by the LSD (lysergic acid diethylamine) counterculture centered in Berkeley and San Francisco. LSD was everywhere and I recall multiple instances in high school where a classmate would admit to attending class under the influence of LSD and try to describe the effects. This seems very rebellious, but in one of the most tragic events of my life, a high school friend jumped in front of a car on the highway after ingesting LSD. He was killed instantly. This event had such a profound effect on me that it eventually drove me toward a career in chemistry – I needed to understand what had happened to my friend. How could the ingestion of a molecule cause such profound effects? Is awareness really just a fragile chemical process that can be so easily tricked?

After the mass closures of the 1980s, Napa State Hospital was one of the few remaining state run mental hospitals in California. If you have seen the movie *One Flew Over the Cuckoo's Nest*, it was filmed at Napa State Hospital. As a child, I would often wonder about the causes of mental illness. I was told that mental illness was the result of a "chemical imbalance" in the brain, but what did that really mean? Could a slight change in a chemical really change our perception of the world?

Similar to many scientists before me, my career in chemistry was driven by a quest to better understand some of the questions that haunted my childhood. Surely, obtaining a degree in chemistry would allow me to understand how hallucinogens work, or what causes mental illnesses. Unfortunately, I was wrong. Chemistry courses seemed to steer clear of any topic of an edgy, dangerous, or unusual nature. In fact, initially learning about these fascinating topics required a course outside the chemistry department. Eventually, a graduate elective course from a psychology department, called "Psychopharmacology," explained the chemical basis for the effect of hallucinogens and the causes of mental illness (I share what I learned in this book).

Later, when I became a chemistry instructor, I made it a point to share these and other stories. It was delightful to find that almost everyone found these topics just as interesting as I did. As I collected new stories, I realized how much of this material was never discussed as part of the numerous chemistry courses required for my Ph.D. Roughly 90% of these stories contained in this book were learned after I graduated. This is where the subtitle of this book, "The stories your chemistry teacher wouldn't tell you" comes from. It seems that there is an overwhelming push to teach the fundamentals of chemistry while neglecting to show the utility of learning the material by connecting it to the real world. Particularly for organic chemistry, there seems to be an aversion of some of these topics, which I feel is because chemists do not want their science associated with anything that poisons you, blows you up, or gets you high. However, these are the topics that many people find exciting (as can be seen by looking at the plot of almost any action movie). Ask a nonchemist where chemicals appear in everyday life and inevitably the answer involves pharmaceuticals, toxins, or illicit drugs.

To share these stories with my students, I usually would take about 5–10 minutes each week to present one of the stories described in this book. For those of you who are teachers or who plan to be, I can say that these stories have been the largest source of positive feedback I have received from my students. Although there is an enormous amount of material that needs to be covered in a typical chemistry course, I say make the time for these extras. It is that important! On multiple occasions, students admitted to me that they only came to class that day so that they could hear the story. Many times, students would speak to me after the lecture to share how that day's story had touched them in some way. One student had been to the emergency room for an acetaminophen overdose, another had a stepfather who was addicted to opioids, and yet another was prescribed amphetamine to treat their attention deficit hyperactivity disorder (ADHD).

You will note that most of the presented stories are short and involve a question or a defined idea. This is done for two reasons: First, I love presenting these questions to my students and trying to evoke an answer from them. Putting students on the spot drives home how little they actually know about the world and how learning chemistry helps them understand their lives. I admit, few things have made me feel more educated than seeing a single simple question stump a classroom with over 400 students. Try it. You will find that very few people know the answers to the questions posed in this book. In addition, some of the cheeky answers I receive have become the highlights of my teaching. Second, I present the stories in a simple format because they will be easy to remember. Jokingly, I tell students to share these stories with their friends and family members so that they can prove that they are receiving an education at Sonoma State University. I am pleased to say that they do just that. An informal poll of my students showed that 90% of them had shared a story at least once, and 75% said that they shared these stories on a regular basis.

Students, like all human beings, want to understand the world around them – they may just not realize it. Telling stories that help students understand and connect to the world they see inspires them in a primal way, making them want to learn and keep coming back for more. This book contains the best stories I have collected over the last 10 years. If you are a teacher, try some of them out and see the profound effect they have on students. Even if you are not a teacher, read on, better understand the world around you, and see how truly strange chemistry can be.

Acknowledgments

To my loving wife, Joy: You are still the most beautiful woman I have ever seen. You are my muse, my life, and the air that I breathe. You are the personification of everything that makes me happy in this world. It was only your love that allowed me to face the adversity I have seen. You have been with me since the start of this journey and I cannot wait to see where life takes us.

To my brother, Richard: Thanks for being the oldest friend I have and for being the funniest person I know.

To my first college chemistry professor, Dr Steven Fawl: Thanks for all of those long talks in your office. Thanks for taking time out for someone who had absolutely no idea what he was going to do with his life. Of all my science professors, you seemed the most worldly and grounded. Your knowledge of chemistry seemed to let you understand the world and how it works. It was because of you that I decided to become a chemist.

To the students of Sonoma State University: Thanks for listening to all of my crazy stories and for continually reminding me why I love teaching so much.

To my colleagues in the chemistry department: Thanks for your help in vetting these stories.

To my agent, Priya Doraswamy of Lotus Lane Literary (lotuslit.com): Thanks for being one of the nicest people I have ever worked with and for helping me realize my dream.

To my editor, Christine Miller (http://tellmewhatyouwanttosay.com): Thanks for all of your encouragement and for helping me find my voice.

To Michelle Sanner: Thanks for your help with the acetaminophen story and helping to start me down the chemical education path.

1

If You Do Not Know Any Chemistry, This Chapter Is For You

As a professor, I regularly teach college-level chemistry courses. These courses present various materials, which are important for students who wish to continue their careers in chemistry. Although most people reading this book will not need all the information covered in these courses, understanding a few key concepts will allow them to understand various ways in which chemistry shows up in everyday life. In fact, one of the driving forces of compiling these stories is to show that even a basic understanding of chemistry can help us comprehend how the world and society work. In particular, I would like to bring readers up to speed on a few key chemical concepts that are referred to in this book (Figure 1.1).

Representing Atoms and Molecules in Chemistry

The first concept concerns the representation of atoms and molecules. Often, the structure of molecules can provide insight into its properties or the ways in which it will affect a human being, if ingested. Certain structural features will imbue molecules with particular properties. In addition, molecules with similar structures will often have similar properties. A detailed understanding of chemistry is not required to make this connection, but only the ability to see similarities.

Chemists represent an individual element with a capital letter, such as "C" for carbon, "H" for hydrogen, and "Fe" for iron, as listed in a periodic table. This letter represents all of the protons and neutrons in the atom's nucleus plus any electrons not involved in bonding. During most chemical reactions, the nucleus of atoms remains unchanged, so this simple representation of elements is helpful to chemists. If an oxygen atom is involved in a chemical reaction, it will remain an oxygen atom. Its structure and bonding may change, but the nucleus will be the same. An important exception is radioactive decay, where a nucleus can be changed and one element can change into another. This will be discussed later.

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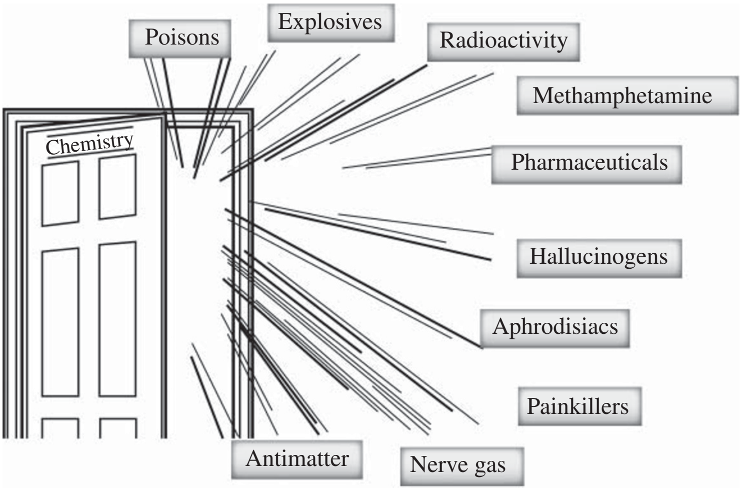
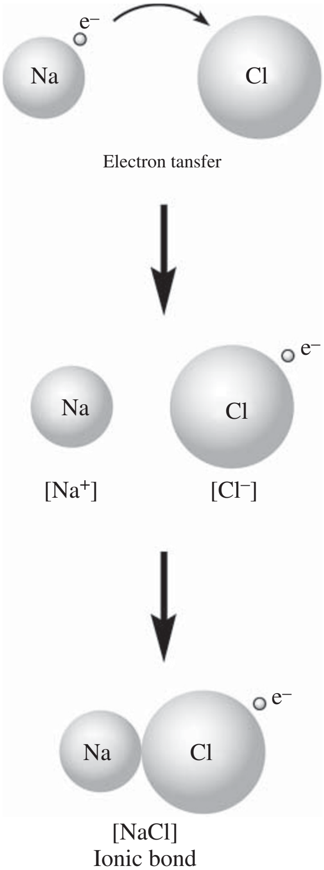


Figure 1.1 Look at what hides behind the door of understanding chemistry.

In the case of some metals and gases, the atom is not bonded (connected) to any other atoms; hence, the bulk material can be represented with the elemental symbol. A block of iron is made up entirely of iron atoms that can be represented by symbol Fe. Similarly, a balloon filled with helium can represented with the symbol He.

Although individual elements are important, chemistry truly becomes interesting when atoms start bonding together to form more complex structures. Two major types of bonds are *ionic* and *covalent*. In an ionic bond, one atom gives up one or more electrons, giving it a positive charge, while another atom gains one or more electrons, giving it a negative charge. Electrostatic forces bring the positive and negative ions together. However, when ionic compounds are placed in an appropriate solvent, such as water, the compounds break apart into their ionic species. The classic ionic compound is common table salt sodium chloride (NaCl). In the crystals of table salt, the sodium and chlorine atoms are being held together by the attraction of a positive and negative charge. When placed in water, table salt tends to break apart into its ionic species, in this case Na^+ and Cl^- (Scheme 1.1).

Ionic compounds are generally made with ionic bonds. Ionic bonds are easily identified because they are made by combining a metal (elements on the left-hand side of the periodic table) with a nonmetal (elements found in the upper right-hand corner of the periodic table). Ionic bonds are typically not formally drawn; rather, the ions are drawn together in a molecular formula where the overall compound is neutral. For example, $FeCl_3$ means a Fe^{3+} ion bonds to three Cl^- ions using ionic bonds. This simple discussion will allow for a better understanding of many ionic compounds with which you may be familiar (Table 1.1).



Scheme 1.1 The formation of an ionic bond in NaCl.

Table 1.1 Some common ionic compounds.

Compound	Name	Ions involved	Common use
KI	Potassium iodide	K^+ & I^-	Treatment of hyperthyroidism
PbO_2	Lead (IV) oxide	Pb^{+4} & O^{-2}	Found in car batteries
$CaCl_2$	Calcium chloride	Ca^{+2} & Cl^-	Road deicing

Covalent bonds differ from ionic bonds in that electrons are shared rather than stolen to form a bond between two atoms. This means that covalent bonds are not easily broken into ionic species and do not break apart when dissolved in water. The sharing of two electrons between two atoms to form a covalent bond is represented with a single line. The water molecule is made up of two H—O single covalent bonds. Similarly, if four electrons are shared between two

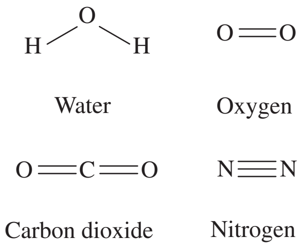


Figure 1.2 The structure of some simple molecules.

atoms, the covalent bond is shown with a double line and is called a double bond. Six shared electrons are depicted by three lines and called a triple bond. Molecular oxygen is made up of a double bond between the two oxygen atoms, and molecular nitrogen is made up of a triple bond between the two nitrogen atoms. Single, double, and triple bonds all have different properties and reactivity that are dependent on the types of atoms involved in the covalent bond. Even now, this basic description of covalent bonds can help you understand the structure of multiple simple molecules (Figure 1.2).

What makes covalent bonds so interesting is their ability to combine to form large molecular structures. Inorganic compounds do not have this ability. Literally, thousands of atoms can be linked together by covalent bonds to create such complex molecules as polymers, proteins, and even deoxyribonucleic acid (DNA).

This book focuses mostly on *organic molecules*, which are typically constructed with covalent bonds. Organic molecules were originally called "organic" because it was believed that these types of compounds could only come from living, organic sources, such as plants or animals. Once it was shown that organic molecules could be made from inorganic materials, the definition was expanded. The current definition states that organic molecules contain the element carbon. *Organic chemistry* is the study of carbon-containing molecules. For the purposes of this book, we will be focusing on the conversion of one organic molecule into another using reactions. Using these reactions, organic chemists create many pharmaceuticals, many plastics, and a multitude of other molecules.

The versatility of covalent bonds creates virtually limitless possible combinations of organic molecules, which is why organic chemistry is such a broad field of study. In college, an entire year of study is devoted to organic chemistry to obtain a typical chemistry degree. At this point, millions of organic compounds are known, with new ones being generated every day. One of the more interesting aspects of organic chemistry is the ability to combine atoms in new ways to make new organic molecules, many of which have never been seen in nature.[1]

1 I am formally trained as an organic chemist. During my career, I estimate that I have created roughly 50 novel organic molecules. These include anticancer drugs, novel polymers, linkers for nanoparticles, and supramolecular agents, which allow for the controlled ordering of molecules.

Because of the large numbers of variations, organic molecules are commonly represented by structures as well as their formal names. In addition, due to a large and complex nature of organic molecules, they are often drawn using a condensed form. Because organic molecules typically have a large number of hydrogens in their structures, it is particularly common to represent hydrogens in an abbreviated form. In a condensed structure, the bonds attached to the hydrogens are omitted and the number of H's is represented with a subscript. Examples of these abbreviations are represented below using some simple organic molecules (Figure 1.3).

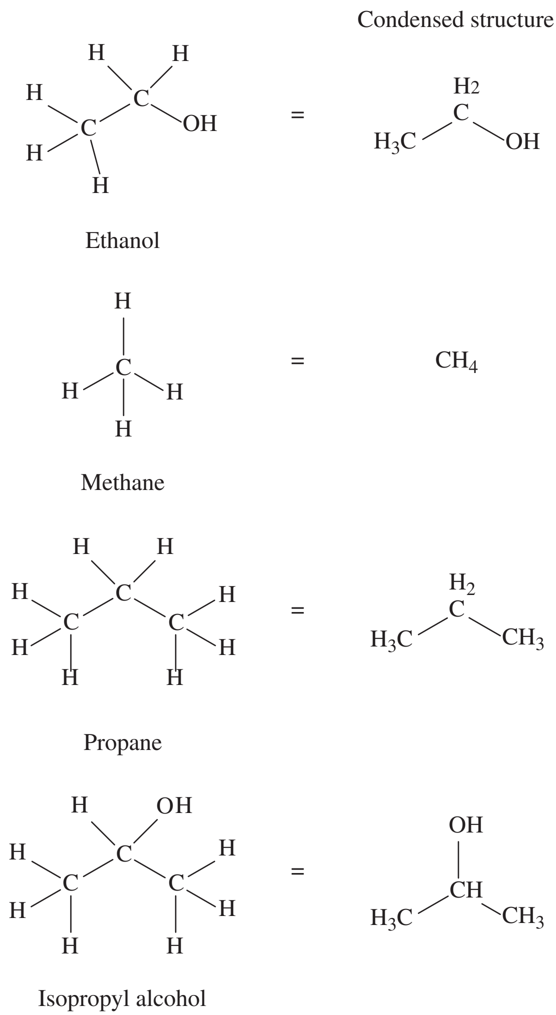


Figure 1.3 The condensed structure of some simple organic molecules.

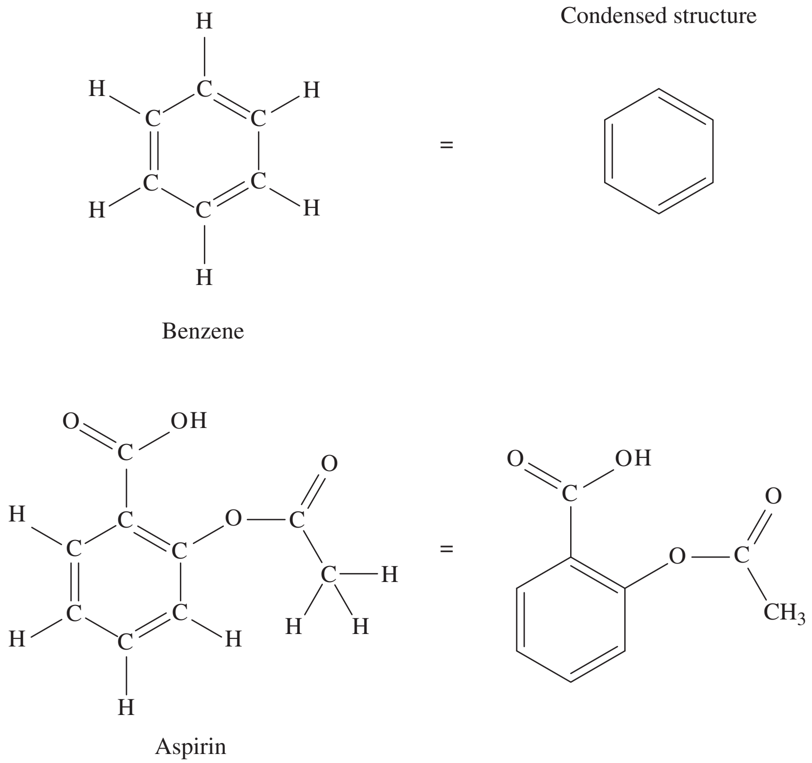


Figure 1.4 The condensed structure of the benzene ring.

Another important way in which hydrogens are abbreviated involves the *benzene* ring. This ring is immensely important in organic chemistry, and its presence can be seen in many important organic molecules. To simplify the structure, the hydrogens at the points of the benzene ring are commonly omitted. Moreover, the carbon atoms in the benzene ring are represented simply by lines denoting the covalent bonds (Figure 1.4).

Lastly, the structures of polymers are usually represented using a type of abbreviation. Small molecules called *monomers* are connected in large numbers during a polymerization reaction to create large molecules called *polymers*. This process is represented in the name “polymer,” which means many monomers. Because polymers are made up of a repeating monomer subunit, they are represented by the subunit surrounded by brackets. The monomer subunit is repeated a variable number of times, which is represented by the

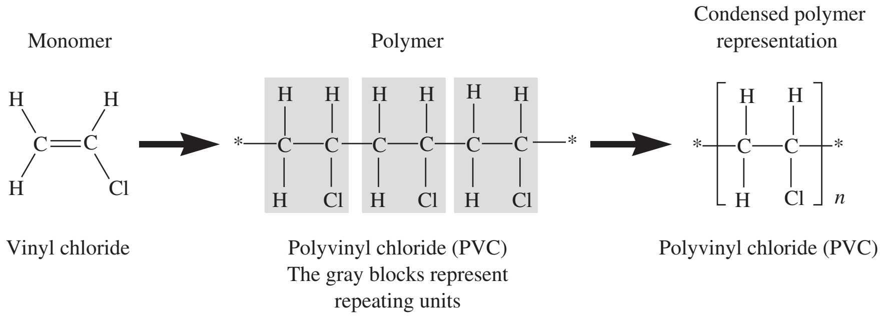


Figure 1.5 How polymers are represented.

subscript "*n*." The actual number of monomers subunits in a polymer is usually unknown, which is why it is represented by a variable (Figure 1.5).

Neurotransmitters

In this book, neurotransmitters are the most important molecules used to describe the function of organic molecules in the body. Virtually everything we do involves neurons communicating with one another. Everything from movement, breathing, and even awareness are brought about by electrical impulses moving across our nervous system. Anyone who has seen a Taser in action knows that neurons are affected by electricity; however, certain chemicals also play an important role in how neurons operate. Many neurons are separated by a small gap called the *synaptic cleft*. During a typical nerve impulse, specific molecules called *neurotransmitters* bridge this gap. When an electrical impulse reaches the end of a presynaptic neuron, neurotransmitters are released and subsequently diffused across the synaptic cleft, binding to the receptors on the receiving postsynaptic neuron. *Receptors* are typically proteins on the surface of the neurons, which recognize and bind to specific neurotransmitters. This binding usually brings about a chemical change that creates an electrical impulse in the receiving postsynaptic neuron. In short, neurotransmitters allow for electrical impulses to be transmitted between adjacent neurons despite the presence of a synaptic gap. By repeating this process, electrical nerve impulses can be sent across the body or across the brain. Neurotransmitters that cause a neuron to fire are considered "*excitatory*" and are responsible for motion, mental

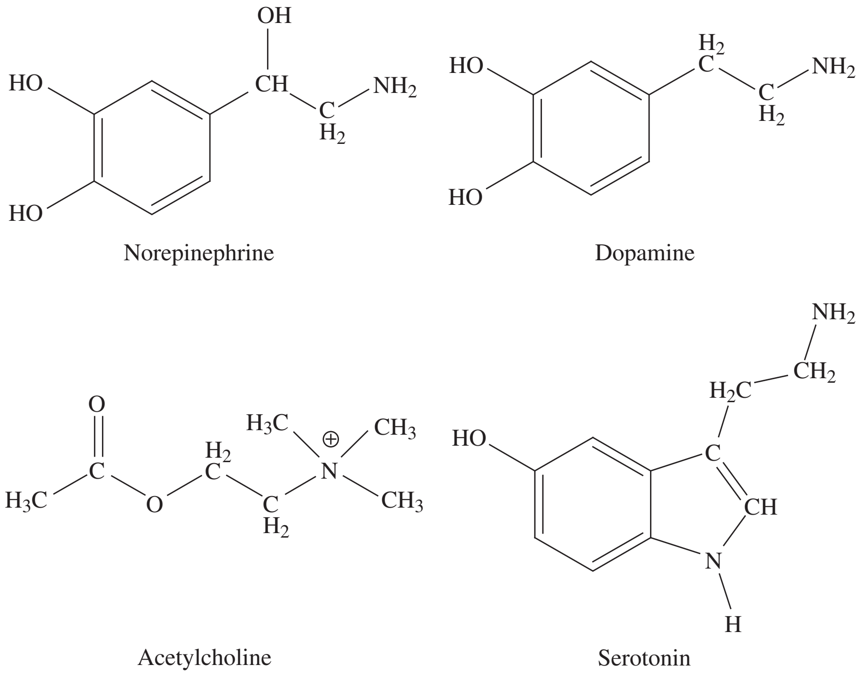


Figure 1.6 Various neurotransmitters.

cognition, and other activities that require the brain and body to be active (Figure 1.6).

In addition, certain neurotransmitters can also be "*inhibitory*" and actually impede the transmission of impulses in neurons. The effect of inhibitory neurotransmitters in these neurons causes a chemical change within the neuron that opposes the effects of excitatory neurotransmitters. In general, inhibitory neurotransmitters are responsible for inducing sleep and filtering out unnecessary excitatory signals.

In short, neurotransmitters send chemical messages between neurons and act as the on and off switches of the nervous system. By understanding that chemicals can affect how neurons work, many interesting concepts can be discussed. Many mental illnesses are believed to be caused by a "chemical imbalance" of neurotransmitters in certain areas of the brain. Many medications used to treat mental illnesses, as well as many psychoactive drugs and neurotoxins, obtain their effects by changing the ways in which neurotransmitters are released and absorbed or by simply mimicking the structure

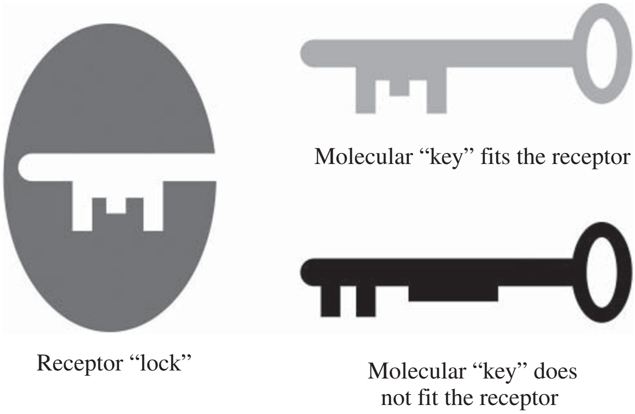


Figure 1.7 A representation of the lock-and-key model of receptors.

of a neurotransmitter. The key receptors in neurons designed to recognize neurotransmitters look for specific structural features. This is called the lock-and-key model. Receptors proteins are typically wadded into a ball-like structure that has small pockets. Certain structural features of molecules allow them to fit into these pockets, activating the receptors. Because the receptors are looking for specific structural features, molecules that have similar structural features can fool these receptors (Figure 1.7).

An excellent example is seen with the molecules dopamine and methamphetamine. Dopamine is one of the most important neurotransmitters in the parts of the brain involving motion and alertness. Key receptors in neurons recognize the benzene ring connected to two carbons and a nitrogen found in dopamine. Methamphetamine also has a benzene ring connected to two carbons and nitrogen, so it can also fit into these receptors, which tricks the neurons into thinking that it is dopamine. The presence of methamphetamine causes the areas of the brain, which utilize dopamine to become excited, causing the hyperactivity and insomnia associated with methamphetamine use. Now that we understand the structural features that can allow molecules to mimic dopamine, we can look for them in other molecules. Ritalin® has these structural features, and it is used to treat attention deficit hyperactivity disorder (ADHD) by stimulating the parts of the brain associated with attention. In addition, the common decongestant pseudoephedrine has these structural features and has the side effects of causing restlessness and insomnia, which has to be stated on the packaging (Figures 1.8 and 1.9).

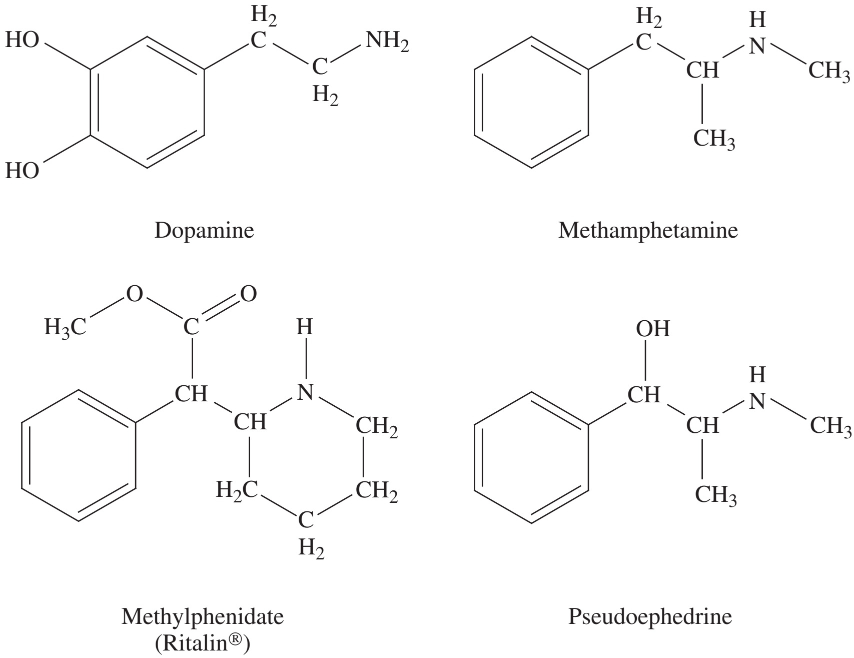


Figure 1.8 Molecules with structures similar to dopamine.

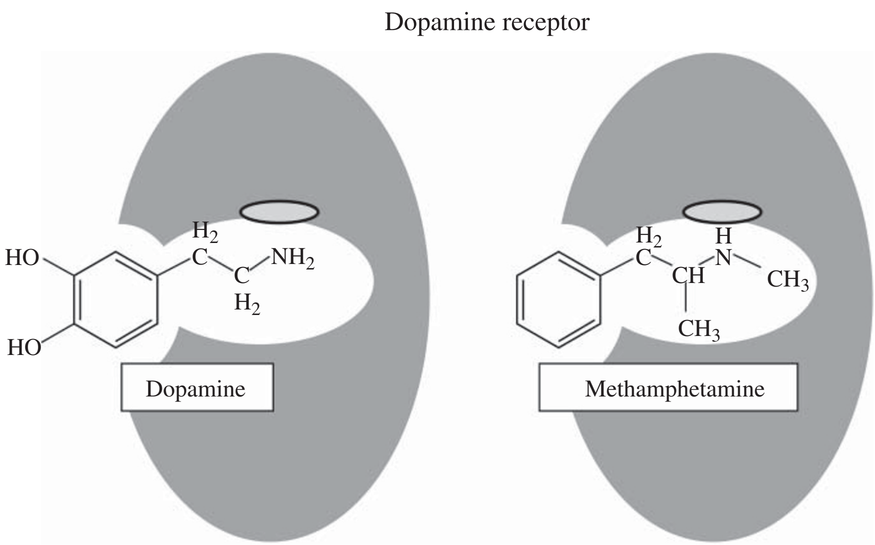


Figure 1.9 A representation of how dopamine and methamphetamine both fit in the dopamine receptor.