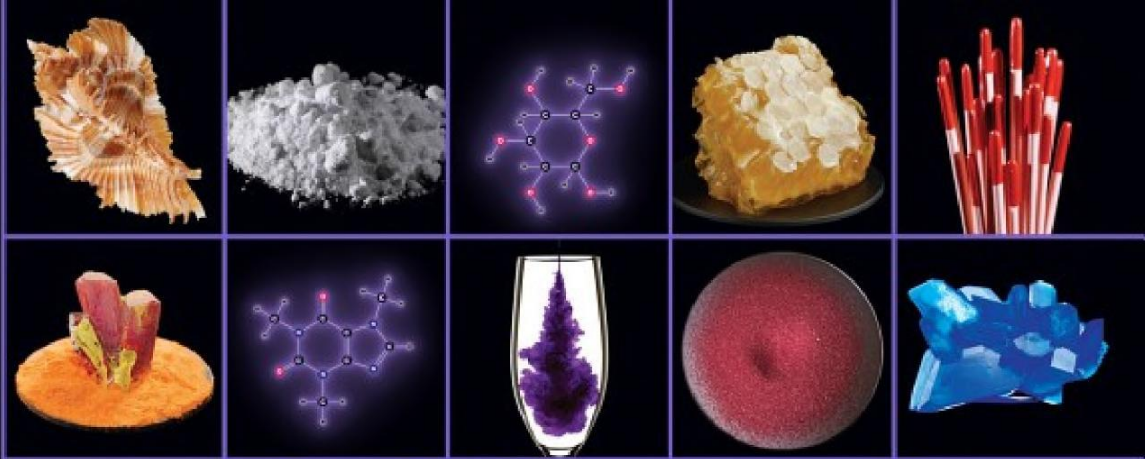


Molecules

The Elements and the Architecture of Everything

"I am so bowled over by *Molecules* that I can only express my feelings with a one-word blurb: 'WONDERFUL!' "—Oliver Sacks

THEODORE GRAY

Author of **The Elements**

Photographs by Nick Mann

Introduction

THE PERIODIC TABLE IS COMPLETE: We know those hundred or so *elements* are all we ever need to worry about. But there is no catalog of all the *molecules* in the universe, and there can't be. There may be only six different chess pieces, but it's out of the question to list all the ways of arranging them on a chess board.

Even putting molecules into logical groups (in order to write a book that at least covers all the categories) is a losing battle. There are almost as many categories of molecules as there are molecules. I take that to mean that I have the freedom to write about only the interesting ones, and the ones that illustrate the deeper connections and broader concepts that unify them all.

If you're looking for a standard presentation of compounds, such as you might find in a chemistry textbook, you'll be disappointed. There is no chapter on acids and bases in this book. I do talk about acids, of course, but in connection with other things that I personally find more fascinating, like soap (which is made by using a strong base to turn a weak acid into a soluble salt that makes oil and water mix).

In that sense this book is more like the one collection of compounds every kid should have: a chemistry set. It’s a little of everything, put together not to be complete, but to be *interesting*. It will teach you something about how the world of chemistry works, and give you a sense of the scope of the subject.

I hope you enjoy reading this book as much as I enjoyed writing it.

Chemistry sets were more popular a few generations ago. It's a common lament of older scientists that kids today just don't have access to the proper tools for discovery and learning. Just *try* to make an explosive using the typical chemistry set you get today. It's almost as if they were trying to make it hard. But as with much lamenting about the world today and all the great things you can't get anymore, a little digging often shows that what you're missing still exists, it's just moved to the internet. This set, a Kickstarter project, is every bit as complete and filled with opportunities for mischief as any set from the past hundred years. Like this book, it doesn't shy away from the more interesting compounds just because they might have a bit of an edge to them. And like this book, it comes with clear warnings about the very real dangers that chemicals pose when handled carelessly or without an understanding of their power.

The world of compounds is so wide and diverse that you could make up a large chemistry set focused on even a tiny fraction of it. This lovely antique set, for example, contains only simple inorganic compounds of interest to someone wanting to learn about the operation of foundries and metal refineries. So it has ores, alloys, clays, fire-resistant brick materials, and other such things. (See Chapter 6 for more about ores.)

Chapter 1

A House Built of Elements

Just two elements, carbon and hydrogen, create an astonishing number of compounds called hydrocarbons. Add oxygen to the mix and you can make a carbohydrate, like this light brown sugar.

ALL PHYSICAL THINGS in the world are made of the elements of the periodic table. I wrote a whole other book about that, and about all the places you can find each of the elements. Sometimes they exist on their own, as in aluminum pans or copper wires. But usually they are found combined with each other in compounds like table salt (which is made of vast arrays of sodium and chlorine atoms in a crystalline grid) or in molecules like sugar (which is made of tightly connected groups of twelve carbon, twenty-two hydrogen, and eleven oxygen atoms).

Molecules and compounds are what this book is all about.

In daily life, we encounter vastly more molecules and compounds than elements (countless thousands vs. dozens) because atoms can connect to each other in so many different ways. Using just hydrogen and carbon, you can make the entire class of compounds called hydrocarbons, which includes oils, greases, solvents, fuels, paraffins, and plastics. Add oxygen to the mix, and you can make carbohydrates including sugars, starches, waxes, fats, painkillers, pigments, more plastics, and a great many other compounds. Add just a few more elements, and you have all the compounds needed to make a living creature, including proteins, enzymes, and the mother of all molecules, DNA.

But what holds these atoms together with such great diversity? And why do I keep saying compounds *and* molecules: is there a difference?

The periodic table is a catalog of all the kinds of atoms that exist or can exist in the universe. Everything is made of these few kinds of atoms, but they can be combined in a huge number of different ways. To learn more about the elements, you can read the whole book I wrote about them called *The Elements: A Visual Exploration of Every Known Atom in the Universe*.

The pure element sodium is a bright, silvery metal that explodes on contact with water. This sodium has been made into the shape of a duck for absolutely no good reason.

Elemental chlorine is normally a gas but can be liquefied under high pressure, as it is in this quartz ampule. Chlorine kills rapidly and painfully on contact with the lungs.

Sodium chloride is a compound, a combination of equal numbers of atoms of the elements sodium and chlorine. Individually, these elements are alarmingly dangerous, but when combined this way, they are as harmless as table salt (which is another name for sodium chloride). Not only are these two elements harmless when combined, but the combination tastes good as well—both to us and to other animals. This is a “salt lick” given to horses to make sure they get enough salt in their diet.

Just two elements, carbon and hydrogen, create an astonishing number of compounds. Well over a hundred thousand molecules made of nothing but these two elements have been studied and given names. Vastly more exist anonymously.

Hydrocarbons include a wide range of liquids, from solvents lighter than water through all grades of oil to the goopiest crank case grease. The more carbon atoms connected together in each molecule, the more viscous the hydrocarbon becomes until eventually the compound turns waxy and finally to solid plastic.

Polyethylene plastic, used in everything from flimsy grocery bags to fancy, cut-resistant gloves, is also a hydrocarbon, made with nothing but carbon and hydrogen. Its molecules contain tens or even hundreds of thousands of connected atoms.

The Force at the Heart of Chemistry

THE FORCE THAT holds compounds together and drives all of chemistry is the electrostatic force. It's the same force that holds a balloon to the wall after you rub it on your shirt or makes your hair stand on end when you shuffle on the right kind of carpet.

It's easy to start describing this force. Any material can carry an electric charge, which can be either positive or negative. If two things have charges of the same sign, then they repel each other. If they have charges of the opposite sign, then they attract each other. (It's a bit like with magnets, where two north poles or two south poles repel, but a north pole and a south pole attract.)

We know a lot about how this force works—how strong it is, how quickly it weakens with distance, how fast it can be transmitted through space, and so on. These details can be described with great precision and mathematical sophistication. But what the electrostatic force actually *is* remains a complete and utter mystery.

It's quite marvelous that something so fundamental is fundamentally unknown. But that's not a practical problem, because a description of how the force works, not a true understanding of it, is all that's needed to make creative use of all the ways that atoms can combine with each other.

A small amount of electric charge accumulates on the surface of a balloon when it's rubbed against another material, such as a T-shirt. When the balloon is near a wall, this charge pulls on charges of the opposite sign in the wall, moving them closer to the surface and leading to an overall attraction between the wall and the balloon. You may hear the term *Van der Waals force* used in connection with molecules: it's the same idea, just happening on a molecular scale rather than a living-room scale.

Two charges with the same sign push each other apart, while two charges of opposite sign pull each other together. The force follows the same inverse-square law that the force of gravity does: if you move the charges twice as far apart, the force between them will be one-quarter as strong.

A Van de Graaff generator accumulates large amounts of electric charge, leading to delightful results. The charge travels along individual strands of hair, causing them to repel each other because they have the same type of charge.

When a negative electric charge (i.e., a large number of electrons) is deposited on the two parts of this device, the repulsive force between the electrons pushes the needle away from the bar holding it. By measuring how far the needle swings, you can measure, crudely, how many extra electrons have been placed on it. Fancier instruments can count individual electrons and measure the forces from them precisely.

Atoms

ATOMS HAVE a small, dense nucleus containing protons and neutrons. The protons have a positive electric charge, and the neutrons have no charge, so overall each nucleus has a positive charge equal to its number of protons.

Surrounding the nucleus are a number of electrons, which have a negative electric charge. Because negative charges are attracted to positive charges, the electrons are held close to the nucleus, and it takes energy to pull them away. We say the electrons are *bound* to the nucleus by their electric charge.

The negative charge on an electron has exactly the same strength, but opposite sign, as the positive charge on a proton. So when an atom has the same number of electrons and protons, the overall charge on the atom is zero; it is a neutral atom.

There's a name for the number of protons in a nucleus: it's called the *atomic number*, and it defines which element you are looking at. For example, if you've got an atom with six protons in its nucleus, you have carbon, and you can make graphite or diamond out of it. If you've got eleven protons in each nucleus, you've got sodium, which you can combine with chlorine to make salt or throw in a lake to make an explosion when it reacts with water.

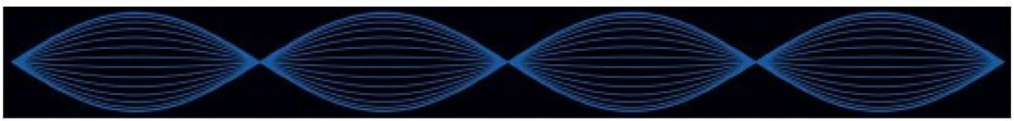
An atom's nucleus determines which element you have, but it's the electrons around the outside that control how that element behaves. Chemistry is really all about the behavior of electrons.

You will often see pictures of atoms that show a small nucleus surrounded by electrons drawn as little balls, with lines that imply they are whizzing around the nucleus like planets around the sun. But those pictures lie. The small nucleus part is OK, but electrons are simply not little balls, and they aren't moving around the nucleus in the conventional sense of the word *moving*. They exist as delocalized objects—puffs of probability—that, in a weird, quantum mechanical way, may or may not be at any one place at any particular time. The best you can do in talking about electrons is to mathematically describe the likelihood that they will be in particular places. And it turns out that these probability distributions have beautiful shapes called atomic orbitals. The electrons don't move around these orbitals, and they are not shaped like these orbitals. Instead, the orbitals, drawn this way, show the likelihood of finding an electron in a given location around the nucleus: brighter areas are more likely to contain an electron, if you were to look there. If you don't look, then the electron is everywhere and nowhere at the same time. Yes, it's very weird. Einstein didn't like it any more than you do, but this math works to describe our world with greater precision than any other theory yet devised. The best you can do is to get used to it.

In an atom with multiple electrons, each electron fits into one of the available atomic orbitals, which fill up in a definite order as more electrons are added. The overall distribution of the likelihood of finding an electron is the sum of all the occupied atomic orbitals. For example, this is what the electron distribution around a magnesium atom looks like. It’s also a demonstration of why you pretty much never see pictures like this in chemistry books: there are twelve separate electrons shown in this diagram, and you can’t make out a single one of them because they blend perfectly into each other, forming a symmetrical, uniform distribution of probability density around the whole nucleus. I’m showing you the picture only to show you why it’s pointless to show you the picture.

Although I hate to have conventional diagrams of electrons as little balls around a nucleus, the fact is that these diagrams are useful because they let you actually see and count the electrons, and they show that the electrons are arranged in “shells” around the nucleus, each of which can hold a certain number of electrons. As the number of electrons around the nucleus increases, the shells fill up one electron at a time from the inside out. It turns out that for nearly all of the elements of interest to us in this book (except hydrogen) the outermost of these shells can hold up to eight electrons. How many electrons are actually in that outermost shell, called the valence shell, depends on which element you have. For example, magnesium, shown here, has two electrons in its valence shell. These valence electrons are what give magnesium its chemical properties. Diagrams like this do *not* represent anything about the actual physical location of any of the electrons! They are just a handy way of showing how many electrons are in each shell, particularly the valence shell.

This bicycle pedal is expensive because it's made almost entirely of atoms with twelve protons in their nucleus. If it were made with thirteen-proton atoms instead, it would cost a fraction as much.



How can an electron be everywhere and nowhere at the same time? Electrons, like many quantum mechanical objects, behave sometimes like a wave and sometimes like a particle.

Imagine the space around an atom as being a bit like a violin string, and the electron a bit like a vibration, a wave, on that string. Where on the string is that wave located? Well, it isn't anywhere in particular on the string, and it's everywhere on the string at the same time. That is, in a sense, the way in which an electron too can be everywhere and nowhere at the same time. When the electron is probed, its behavior becomes more like that of a particle, and it materializes, or localizes in the language of quantum mechanics, in a particular spot.

Looking at this diamond again, now we know that it's a diamond *because* its atoms all have six protons in them. Graphite might seem like a completely different substance, but its atoms also have six protons in each nucleus, so it too is made of carbon. Notice that carbon has four valence electrons in its outermost shell, with room for four more. This fact is *crucial* to the existence of life on earth, and to most of the rest of this book.

Almost all the atoms in this duck have eleven protons in their nucleus; they are sodium atoms, so this is a sodium duck. A few on the surface have only eight; those are oxygen atoms from the air that have combined to form the compound sodium oxide, a white powder. Throughout the duck there are a few atoms with various other numbers of protons; those are contaminants, elements other than sodium that have no business being in a sodium duck. Notice that sodium has a single, lone electron in its outermost shell. This fact singlehandedly explains nearly all of sodium's chemical behavior.

The atoms in this liquefied chlorine have seventeen protons in them. Notice that the outermost shell of electrons in chlorine is missing one electron. That tells you just about everything you need to know about chlorine's chemistry.

The atoms in the neon gas in this indicator light have ten protons. Notice that the outermost shell of electrons is completely filled. This makes neon an extremely un-reactive element: When an atom's outermost shell is filled, it is in a happy place.

Compounds

THE ELECTROSTATIC FORCE is what holds electrons and protons together in a single atom, and it's also what holds atoms to each other in compounds and molecules. When an individual atom has exactly the same number of protons and electrons, it has no overall charge, so there's no electrostatic force between it and any other neutral atom. To get them to connect to each other, you have to move the electrons around from one atom to another, creating an electrostatic force between them.

Look again at the atomic diagrams on the previous pages. Notice that some of them (such as neon) have "full" outer shells, while others (such as carbon, sodium, and chlorine) have gaps that indicate missing electrons. Each shell has a fixed number of electrons that it can hold (either two or eight, depending on which layer it is). The inner shells fill up completely, but there may not be enough electrons to completely fill the outermost, or valence, shell. When that shell is not full, you are dealing with an unhappy atom, and you have a golden opportunity to move electrons around.

Atoms are willing to go to great lengths to get a complete shell, even if that means not being electrically neutral anymore. But they do have preferences. Some like to fill in holes with extra electrons, while others choose to shed a few stragglers in their outermost shell. Still others prefer to share electrons with neighbors in a way that allows a single electron to, at least partially, satisfy two atoms at once.

Any time you have two or more atoms connected to each other, it's called a molecule. If there are at least two different kinds of elements in your molecule, then it's also called a compound.

Atoms of sodium and chlorine are very happy to exchange electrons to form sodium chloride. In this context, “happy” means that, as the electrons move into their favorable arrangement, the process releases a lot of energy. Chemical reactions that release energy do so in the form of heat, light, and sound. The more happy elements are to combine (i.e., the more energy they release when doing so), the less likely you are to find them in isolation in nature. Highly reactive elements like sodium and chlorine are absolutely never found that way: if you see pure sodium or pure chlorine, you know someone has gone to a lot of trouble to tear them out of their happy union with other elements.

Here are the diagrams for sodium (eleven protons) and chlorine (seventeen protons) again. Notice that in both of them the outermost shell of electrons is incomplete. Sodium has room for eight electrons in its outer shell, but only has one. Chlorine also has room for eight, and is missing only one. Sodium and chlorine are very angry about this; both of them are *very* reactive substances that viciously attack anything in their vicinity. Sodium rips up any water it comes near, while chlorine contents itself with ripping up your lungs if you breathe it.

Moving a single electron from a sodium atom to a chlorine atom solves both their problems, because each now has a filled outer shell. (The completely empty shell drawn around sodium is only to show where the electron used to be: what counts is the filled shell just inside it.) Once the electron has moved, the sodium atom has a positive charge, while the chlorine atom has a negative charge. Because the atoms now have opposite charges, they are attracted to each other. They stick together to form a compound known as sodium chloride, or, more commonly, table salt.

When atoms have an electric charge, as in salt, they are called "ions." The sodium ion has a +1 charge (i.e., it's missing one negatively charged electron), while the chloride ion has a -1 charge. The bond formed between two ions is called an ionic bond, and compounds formed out of ionic bonds are called ionic compounds. Sodium chloride, thus, is an example of an ionic compound. Many compounds have this kind of bond, and many of them are known generically as salts. Because there are only two kinds of charge, positive or negative, compounds held together exclusively by ionic bonds are always pretty simple. Each negative charge attracts all the nearby positive charges indiscriminately, and vice versa. So the elements pack together as tightly as they can in a simple repeating arrangement called a crystal. Shown here is a sodium chloride crystal. If you strictly follow the definition of a molecule as any set of atoms bonded to each other, an entire grain of salt is a single molecule. But usually people shy away from this idea and say the salt grain is an ionic crystal, not really a molecule.

Molecules

SODIUM AND CHLORINE form *ionic* bonds because chlorine really wants to acquire an extra electron, and sodium is very happy to be rid of what it considers an excess electron. Other atoms are less strong-willed: rather than gain or lose electrons altogether, they prefer to share electrons with each other. When atoms share one or more electrons, they form *covalent* bonds.

Covalent bonds allow for complicated structures because, unlike ionic bonds, they are personal; they exist between specific pairs of atoms.

Each kind of atom has a characteristic number of electrons that it likes to share with neighboring atoms. For example, carbon, which is missing four electrons from its outer shell, likes to take a share of four electrons from other atoms so that it can pretend it has a full outer shell of eight. Oxygen likes to take a share of two. Hydrogen is incredibly generous: it has only one electron but is happy to share it with other atoms.

These rules allow atoms to work like LEGO® blocks that snap together in particular ways. And when they do, the result is called a molecule.

Carbon has four electrons in a shell meant for eight. This means carbon is often found bonded to four other atoms, sharing electrons with each of them to complete its shell.

Hydrogen has one electron in a shell meant for two. That means it likes to bond with a single other atom.

When four hydrogen atoms combine with one carbon atom, the result makes all of the atoms fairly happy. The outer shell of the carbon atom is populated with a total of eight electrons, four of them from the carbon and one from each of the four hydrogens. The carbon pretends all eight electrons belong to it, creating a full shell, while the hydrogen atoms each pretend they have two electrons to fill their own shells.

A group of atoms arranged this way is called a methane molecule.

The fuzzy diagram above doesn’t represent the real locations of electrons in a methane molecule, but it does conveniently let you count them and see how they fill up the atoms’ outermost shells. A more schematic form of this diagram is called a “Lewis dot” structure. Each dot represents one electron in the valence shell. You will find Lewis dot structures in chemistry textbooks explaining why particular kinds of atoms bond in particular ways.

Showing all the individual electrons in the atoms that make up a molecule, either fuzzy or as Lewis dots, quickly becomes impractical. Therefore we are going to draw molecules the way you usually see them in chemistry books, with lines that show where electrons are being shared. Each line represents one pair of shared electrons. I've left a soft glow around the lines as a reminder that they are symbolic and do not reflect what the atoms actually look like. There are no strings or rods in a real molecule, only fuzzy, diffuse electrons swimming around and between the atomic nuclei, gluing them together with electrostatic force.

Carbon atoms can bond with each other by sharing one, two, or three electrons, resulting in a single, double, or triple bond. Each shared electron uses up one of the four "slots" carbon makes available for bonding. The remaining slots are often filled with hydrogen atoms. Multiple bonds are stronger and shorter but also more reactive. These compounds, in order, are the flammable gas ethane (single bond), the very flammable gas ethylene (double bond), and the explosively flammable gas acetylene (triple bond).

One of carbon's best tricks is that atoms of it can be assembled into rings of any size. Sixmember rings are especially common and important. Notice how the first example to the right (cyclohexane) has two hydrogen atoms sticking off each carbon atom, while the second and third examples (which are both benzene) have only one. That’s because the carbon atoms in benzene are sharing an average of one-and-a-half electrons with each neighbor, while the carbons in cyclohexane are sharing only one. Benzene rings occur *all over the place* in the world of organic compounds. Although you will often see them drawn with three double and three single bonds (as I did on the far right), this is a fiction: in fact the three extra bonding electrons are spread evenly throughout the center of the ring, so a circle is a more accurate way of depicting the bonds inside the ring. Both styles are commonly used, except in this book where I use only the circle style, which I think looks and communicates better.

Most of the interesting compounds in this book are made out of just a few kinds of atoms. To see how this is possible, consider just how many ways there are of arranging carbon and hydrogen, using no more than four carbon atoms. There are a full *fifty* ways to do that! Some of the arrangements are very common, some of them are exotic, and some of them would be nearly impossible to assemble. Most of them have in fact been made, studied, and given names.

An Architecture of Atoms

CHEMICAL DIAGRAMS like the ones we've been looking at show how atoms are connected to each other. They make molecules look flat, which is not the case at all: molecules are very three-dimensional objects. However, drawing the structures to appear flat makes it easier to see how each atom is bonded to its neighbors, so that's how people usually draw them.

Physical models can show the real, three-dimensional shapes of the molecules. Computer renderings can do the same, especially when displayed live on a computer screen so they can be rotated and zoomed.

Chemists continue to use physical models for relatively small molecules. But before computers took over the job of displaying giant molecules, they too were made into physical models. This model of a tiny fragment of DNA was built by Francis Crick and James Watson to explore how its atoms might fit together. When they eventually got it just right, they used this model to explain to the world that DNA was a double helix.

This diagram of the molecule known as gabapentin, a drug used to treat nerve pain, shows how its atoms are connected together. It's a logical mapping of what kinds of atoms are in the molecule and how they are bonded to each other. But it really doesn't show the three-dimensional structure well at all.

This plastic ball-and-stick model of gabapentin shows its three-dimensional structure reasonably well, but only if you can turn it around; from any one viewpoint, some parts are hard to make out. As with flat diagrams of molecules, the lines are a lie: there are no rods and no hard spheres in a real molecule.

Space-filling models like this one attempt to reflect more accurately the reality that electrons are diffuse clouds of probability that wash around and through each other. Space-filling models can help visualize why some configurations of atoms (i.e., some molecules) are much harder to make than others. Sometimes the atoms just don’t fit easily into the available space.

An Explosion of Possibilities

IT'S ASTONISHING how much of chemistry involves only about half a dozen elements. Pretty much the entire fields of organic chemistry and biochemistry are to do with carbon, hydrogen, oxygen, nitrogen, sulfur, sodium, potassium, and phosphorus, with a very few other elements showing up from time to time and in relatively small quantities.

A greater diversity of elements is found in the world of inorganic compounds, but quite frankly the entire range of interesting inorganic compounds would fit in a small corner of one room in the house of chemistry (sorry, inorganic chemists). The real action in modern chemistry is centered on carbon, because carbon is the element of life—the basic building block of the great majority of molecules that are significant to living things.

In the remainder of this book, we will visit the rooms of the house of chemistry, the house built of elements. It is lovingly decorated with molecules, organic and inorganic, safe and unsafe, beloved and despised. Just as every living creature has a place and a role (even mosquitoes), so too every compound wants to be known and appreciated for what it contributes to the richness of the natural world (even thimerosal).

In Chapter 2, we'll learn about sweet oil of vitriol and how chemical compounds have three names.

In Chapter 3, we'll learn how the synthesis of this compound forced everyone who understood it to rethink the deepest questions of life.

In Chapter 4, we'll learn how fatty acids help keep you clean.

In Chapter 5, we'll learn why this stuff is so icky.

In Chapter 6, we’ll learn where compounds come from.

In Chapter 7, we'll learn about a molecule shaped like a shoe.

In Chapter 8, we'll learn what these darts are used to inject and about the power of poppies.

In Chapter 9, we'll learn why one of these bowls is so much smaller than the other.

In Chapter 10 we'll learn why natural vanilla extract is radioactive, but synthetic vanilla is not.

In Chapter 11 we'll learn what this device is used for.

In Chapter 12, we'll learn why being colorful is a rare thing for a molecule.

In Chapter 13, we'll learn why this molecule caused a dangerous movement.

In Chapter 14, we'll learn about molecules that are more like computers than molecules.

Chapter 2

The Power of Names

A vile and fuming substance, but what is its name?

I DECIDED TO take a class in organic chemistry for what was quite possibly the silliest of reasons: I liked the names of the compounds. It wasn't so much the sound of them, but the fact that assembled together they form a system that connects to a deep and beautiful body of knowledge. As I considered what these names mean and how each one gives meaning to the others, for the first time I truly appreciated the power that comes from giving a thing a name.

Just as T. S. Eliot said of cats, many chemical compounds have three names.

If they have been known for a long time, they have an ancient, alchemical name. These poetic names usually describe where the stuff comes from rather than what it is, because back then no one really had any idea what they were working with.

For example, in the alchemical language, sweet oil of vitriol is obtained by distilling oil of vitriol with the spirit of wine. (And oil of vitriol, in case you didn't know, is the liquid obtained by roasting green vitriol. The spirit of wine is the first thing that evaporates when you heat wine.)

I love these names for the images they form of wizards and potions, but they don't tell you the first thing about the true nature of the substances they refer to.

The alchemists, though commonly looked down on today as superstitious quacks trying to turn lead into gold, were actually serious students of nature who made many early discoveries. They set the stage for the emergence in the 1700s of the modern science of chemistry.

Alchemical Names

HERE ARE TWO chemical reactions written out using the alchemical names for each substance. This language sounds beautiful, but what does it mean? Notice that oil of vitriol appears on both sides of the second reaction: it isn't actually consumed or altered in this process but must be present in order for the spirit of wine to be transformed. Why?

This image shows green vitriol in a modern glass retort, a transparent version of the clay retorts that would have been used to roast this material in ancient times. But what *is* green vitriol? The name connects to history but not to other chemicals. It is a dead-end name.

Oil of vitriol, a vile and fuming substance, is the origin of the word *vitriolic*, which refers to the sort of vile, fuming criticism you hear among politicians when they should be talking to one other like civilized people. It's a great image that accurately depicts both politicians and this particular substance. But what *is* oil of vitriol?

Distillation of wine into spirits is one of the oldest of all chemical processes. It is the physical separation principally of two compounds, water and the spirit of wine. You can probably guess the modern name for the spirit of wine.

Sweet oil of vitriol is sweet indeed, but its seductive nature can be dangerous.

Common Names

COMPOUNDS IN WIDE use today all have common names by which they are known and traded. Today we know oil of vitriol, for example, as battery acid, chamber acid, or Glover acid, depending on its concentration. You have probably heard of battery acid. Although the name tells you *how* it is used, does it really tell you anything about *what* the substance is?

Sweet oil of vitriol is common ether, which has been used as a surgical anesthetic in the past. Green vitriol doesn't have a modern common name, but it is sometimes known by its mineral form, rozenite.

Spirit of wine is, of course, grain alcohol. Again, this name is familiar. You may know that there's an important difference between grain alcohol and wood alcohol, but what is that difference?

To really understand these substances, you need to know their third name—the kind of name that gives you power over a thing.

Written this way, the reactions appear more familiar, but they still don't make a whole lot of sense. Why on earth would battery acid plus booze give you a gas that knocks you out? Well OK, maybe that does make a certain kind of sense, but why, *chemically*, would it do that?

Rozenite is a mineral form of green vitriol. I still haven't told you what it is.

Battery acid is a strong acid used in lead acid batteries for cars. But telling you what it's used for doesn't tell you anything about what it is.

The purest form of alcohol you can buy for the purposes of human consumption is 95 percent grain alcohol and 5 percent water. (The "proof" of an alcoholic beverage is just the percentage of alcohol multiplied by two, so this stuff is sold as 190 proof alcohol.)

As the first "anesthetic" used in surgery, ether was an incredible advance in medical science. Prior to the introduction of ether in the mid- 1800s, standard procedure was to drink brandy, bite down on something, and hope your surgeon worked really, really fast because you were going to feel every cut.

Systematic Names

IN THE EARLY 1800S, it became clear that chemical compounds were different arrangements of specific types of atoms in definite proportions. For example, today we know that green vitriol is composed of molecules that contain exactly one iron atom, one sulfur atom, and four oxygen atoms. Further, we know that the four oxygen atoms are strongly bonded to the sulfur atom and that this group of five atoms is bonded in a different way to the iron atom.

All this information is encoded in the separate parts of the modern systematic name for green vitriol, iron(II) sulfate, and its chemical formula, $FeSO_4$. Let's pick apart this particular name.

"Sulfate" always refers to a group of four oxygen atoms around a single sulfur atom; that's the SO_4 part. You will find this name embedded in the names of countless compounds (we'll see examples later on). "Iron," of course, refers to the element iron, whose symbol, for historical reasons, is Fe. The (II) refers to the electric charge the iron atom has in this particular compound, positive two, meaning it gave up two electrons when the compound was formed.

Each of the compounds in these reactions has a modern name that encodes deep knowledge about its true nature. We’ll look at each one in more detail over the next few pages. Systematic names help us understand the substances and, more importantly, understand why they transform themselves in the particular and repeatable ways they do.

The power of these names is at the very heart of chemistry.

Using modern systematic names and chemical formulas makes clear what is happening in these reactions: the exact same elements appear on both sides in the same numbers (i.e., the equation is balanced). The elements are simply being rearranged into new groupings that represent new compounds. See how, in the reaction below, the two smaller molecules of ethanol are merged into one large molecule of ether, with a water molecule left over where they joined? *That explains so many things!* See how H_2SO_4 (sulfuric acid) appears unchanged on both sides of the reaction? That means it's a *catalyst* that causes the reaction to happen but is not consumed in the course of the reaction (though it does become more and more diluted by the water that is created by the reaction).

Roasting green vitriol (iron(II) sulfate) with water to create oil of vitriol (sulfuric acid) *means* this reaction.

Heating oil of vitriol (sulfuric acid) with the spirit of wine (ethanol) *means* this:

Now that the identity of specific chemicals is clearly understood, each can be separated, purified, and packaged individually. All of these are commonly available, though, amusingly, it's easier to buy pure diethyl ether than pure alcohol, entirely for tax reasons. (Alcohol that you can drink is very heavily taxed, so almost all alcohol sold for nondrinking purposes is “denatured” with about 5 percent methanol and isopropanol, which makes it poisonous and allows it to be sold without tax. Alcohol sold for drinking purposes always has about 5 percent water because it’s expensive and pointless to purify it the rest of the way if it is intended for drinking. When you need totally pure alcohol, you have to pay both the tax and the cost associated with removing the water.)

You may have noticed that we added an extra compound in the reaction above, FeO or Iron(II) oxide. This is an oversimplification. The reaction is more likely to produce some combination of different iron oxides such as Fe_2O_3 (iron(III) oxide) or Fe_3O_4 (Iron(II, III) oxide), but that’s not important. The point is that knowing the chemical formula for the reactants and products made it obvious that the previous representations of the reaction were incomplete. The old names did not capture the essential truth that all substances are made of elements and that those elements are eternal. What you put in must balance perfectly with what comes out, because chemistry is a game of rearranging atoms, not creating or destroying them.

Where Names Take You: **Salts**

THE WONDERFUL THING about systematic names is that they invite variation. Start with green iron(II) sulfate ($FeSO_4$), change the “II” to a “III”, and you get a yellow powder, $Fe_2(SO_4)_3$. Each SO_4 group still has a -2 charge, but each iron atom has a +3 charge, so in order to get the charges to add up to zero, you need two irons for every three sulfates.

Replace the iron with copper, and you get copper(II) sulfate, which grows into lovely, big, blue crystals. Stick with iron but substitute carbonate (CO_3) for the sulfate, and you get iron(II) carbonate, which makes pale, lustrous crystals. Substitute both and you get copper(II) carbonate, the green of weathered copper.

All of these compounds are examples of mineral salts. From their systematic names, you can tell exactly what elements they are made of and in what proportions.

Iron and sulfate in a two-to-three ratio yields the yellowish power known as ferric sulfate, iron(III) sulfate, and various mineral names—none of them particularly common and all of them of mixed composition.

$Fe_2(SO_4)_3$

A sulfate group plus iron in equal numbers gives the green substance known variously as green vitriol, ferrous sulfate, iron(II) sulfate, and the mineral rozenite.

$FeSO_4$

Copper(II) sulfate, also known as cupric sulfate, likes to grow into rather large, blue crystals. Large individual crystals are sold as specimens, but even the stuff sold in fifty-pound bags is nicely crystalline. I have a bag like this I got for killing algae in my lake but never used because I found out copper sulfate was harmful to frogs.

$CuSO_4$

Calcium sulfate takes various forms depending on how much water is bound up in its crystal structure. The form with two water molecules per calcium sulfate unit is called gypsum, also known as chalk when made into sticks for writing on blackboards.

$CaSO_4$