Chemistry for future presidents (and the teachers that will teach them)

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Paradoxes

Most of everything is nothing. The world is made up of atoms which consist of protons, neutrons, and electrons. Even though atoms are tiny, these pieces are even tinier. If you had an atom the size of a baseball stadium, the nucleus would only be the size of a mosquito. Electrons are even smaller than that. Everything else would be empty space.

No matter how hard you try, you can never actually touch something. Even though you can feel your cat's soft fur or the impact of a brick wall that you accidentally walked into, no two particles ever actually touch. The electrons in your body and the electrons in a brick wall are all negatively charged. The identical charges repel one another with incredible force as they get close to one another, stopping your electrons from ever touching the wall's electrons.

Without electrons, there would be no lollipops. Candy is made up of sugars such as sucrose, a combination of 12 Carbon atoms, 22 Hydrogen atoms, and 11 Oxygen atoms. Only in this unique combination do you get all of sugar's wonderful properties. Leave out just one carbon atom, and you could end up with 11 molecules of formaldehyde ($11xCH_2O$), the smelly preservative of dead frogs in biology classrooms. What causes these atoms to stick together in this specific combination? It's each atom's quest to have the perfect number of electrons!

You can turn lead into gold, *if* you know how. For centuries, alchemists have tried this seemingly impossible task. With a knowledge of atoms and chemical bonding, modern scientists have finally figured out how to do it. By the end of this chapter, you will understand how.

The structure of the atom

Reread the following brief sections of Physics for Future Presidents by Richard Muller to review the parts of an atom: pages 2-1 through 2-2 and 4-1 to 4-4 (stop at horizontal line). I summarized the key components of an atom in the table below.

Particle	***Mass***	***Electric charge***	***Size***	***Location***	***What it does***
Proton	About 1 AMU[1]. 2000 times heavier than an electron.	+1 (positive)	Smaller than $1/100{,}000^{th}$ the size of the whole atom.	In the nucleus	Determines almost all the properties and behaviors of the atom.
Neutron	About 1 AMU. A tiny bit heavier than a proton.	0 (neutral)	Similar to a proton.	In the nucleus	Helps make the nucleus stable.
Electron	Very light. Almost 0 AMU.	-1 (negative)	Unbelievably tiny. Much smaller than a proton or the nucleus.	In orbitals in a "cloud" surrounding the nucleus	Determines which atoms will form chemical bonds with which one another.

[1] AMU = Atomic Mass Unit. Because atoms are so small, it's convenient to have a special unit of mass for things of their size. Convert AMU to kilograms using 1 AMU = $1.66x10^{-27}$ kg.

Protons and neutrons exist in the tiny nucleus of the atom. Almost all an atom's mass is packed into the nucleus, which is less than 1/100,000th the size of the entire atom. Understanding the size of the nucleus helps you understand the first paradox that "most of everything is nothing."

Protons are the single most important thing that defines whether an atom is gold, lead, chlorine, or something else entirely. The building blocks of those three elements (and all the others) are protons, neutrons, and electrons. If you could magically strip away all of the electrons from a gold bar, you'd still have a gold bar. (Atoms regularly lose their electrons, though it would be pretty hard to strip all of the electrons out of an entire gold bar.)

At times, neutrons seem boring – they don't have any electric charge, they don't play a role in chemical bonding, and they don't affect most physical properties like color, ability to conduct electricity, crystal structure, etc. Before you vote them off the island, you should value their important job of holding the nucleus together. If a nucleus has the wrong number of neutrons, it can become unstable and the entire thing could fall apart (causing radioactivity, discussed by Physics for Future Presidents, Chapter 4). If you added just one neutron to every atom of gold in your gold bar, it would stay gold for a while[2], but one-by-one, the atoms would eventually decay into something else (mostly mercury like you find in thermometers).

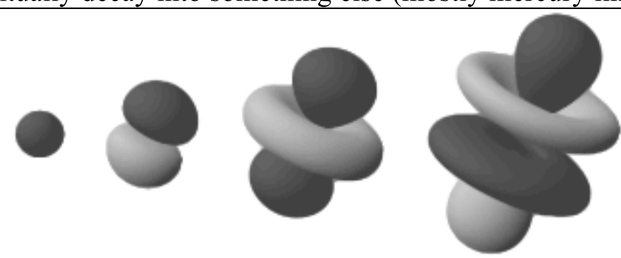

Figure 1. The weird "shapes" of the outermost electron orbitals for different sized elements. (bigger elements to the right)
From: http://en.wikibooks.org/wiki/General_Chemistry/Shells_and_Orbitals

A typical chemistry textbook might tell you that electrons "orbit" the nucleus in specific "shells" and each shell can only fit a certain number of electrons. Using this simple analogy of electrons orbiting atomic nuclei that reminds one of a mini solar system, physicists were able to explain a lot of features of the way chemical bonding works. It turns out that this simple model is wrong. Electrons are bafflingly complicated and the field of quantum mechanics arose to try to describe their behavior (I've devoted an entire section to them below called "The Secret Lives of Electrons"). The electrons don't move around in circles like planets in a solar system. In fact, it's nearly literally impossible to describe the motion of electrons, but they certainly do move from place to place as you observe them. The idea that electrons exist in specific shells is mostly correct, but the spaces have such complicated shapes that we call them 'orbitals' rather than 'orbits' or 'shells' (see Figure 1). Each weird shaped orbital can only accommodate a specific number of electrons, but not because there isn't enough room for more (see Secret Lives section again for the real reason). What you need to know about the structure of the atom is that there is a positively charged nucleus with protons and neutrons and sea of negatively charged electrons moving about in different orbitals with a maximum number of electrons in each orbital.

As atoms add electrons, they build up more and more orbitals, always filling one orbital before utilizing the next one. Most orbitals have room for a total of 8 electrons each, so a big atom like lead that usually has about 82 electrons will have electrons in ten orbitals. The last or "outermost" orbital will have only two electrons in it. As we'll see later, this last orbital turns out to have a very big impact on the behavior of atoms.

[2] The half life of Gold-198, a version of gold with one more neutron than the most common naturally occurring version of Gold-197, is about 2.6 days. At that rate, you'd expect 99% of your gold to have decayed after a month.

Electric force

Reread the following brief section of Physics for Future Presidents by Richard Muller to review the electrical charge of different parts of the atom: pages 6-2 to 6-3 (stop before "Electric currents -- Amps").

Electric force can pull together or push apart particles with incredible strength, and atoms are filled with particles having electric charge. It's no wonder that an atom's charged particles, its protons and electrons, can have such a big impact on its behavior. With electric forces, you need to know that *opposite charges attract one another* and *identical charges repel one another*. An electron with its negative charge should be attracted to a proton's positive charge, which is the main reason that electrons bother hanging out inside atoms in the first place. Both electric forces and gravity draw the two particles together, so why don't they just collide? It turns out that there are other more complicated forces at work inside the tiny atom that prevent a collision. Nonetheless, electrons are most likely to be found very close to the nucleus -- even for electrons in what we call an atom's "outermost" orbital.

Under typical conditions, atoms like to have the same number of positive particles as negative ones (making them electrically neutral). If they weren't neutral, they would attract other particles to them by the electric force. However, "chemistry" is all about atoms trying to change the number of electrons they have. Stay tuned.

Chemical Bonding: Don't worry, be happy!

People often refer to "chemistry" in a relationship, and this section talks all about why. Atoms typically don't float around by themselves. Instead, they are usually bonded to other elements. You have probably heard the chemical formula for water of H_2O. That means that two hydrogen atoms are bonded together with one oxygen atom. In a moment, we'll see what a chemical bond actually means. We'll find that chemical bonds share some things in common with relationships between people -- you want to bond with the right person that complements your strengths and you want both people get something valuable out of the relationship. Some chemical bonds are really strong and last a long time, but others are more fleeting and the atoms will leave to go into another bond if that situation looks more appealing. Whenever bonds are broken or new bonds form, we call that a **chemical reaction**. During all those experiments you did in a high school chemistry class, you were trying to get atoms to bond together, or to change who they were bonded to.

You would think that an atom could be happy by simply having the same number of negatively charged particles (electrons) as positive ones (protons) -- being "electrically neutral". But that's not enough! Every atom not only wants to be electrically neutral, but they desperately want to have their outermost orbital filled with the maximum number of electrons allowed -- neither more (which is not possible) nor less (which is terribly depressing). When an atom has the perfect number of electrons, I like to say that the atom is "happy." This is not a technical term and other scientists don't use it. I made it up because I think it captures the essence of the process. You may also use the word, but you must also know what actually makes atoms happy so that you can explain it to someone else. All of chemistry from acids neutralizing bases to gasoline bursting into flames when combined with oxygen is about making atoms happy.

To be honest, scientists don't fully understand why having the perfect number of electrons makes an atom happy. The general reason is that a full outermost orbital is the state with the lowest amount of energy. In nature, things always prefer to end up in the state with the lowest energy. For example, if you place a ball at the top of the stairs, it will bounce down to the bottom of the stairs where it has much less potential energy. If you add energy to an atom, it usually gives that energy off in the form of light so that it can return again to its original, lower energy state (which is basically what happens when you pump electricity into a light bulb). When scientists calculate the energy states for an atom, the lowest energy comes when you have all electron orbitals filled to capacity (including the outermost orbital, which is the only one that might not be filled). Just like the ball on the stairs rolls to get downstairs and the atom in the lightbulb emits excess energy as light, an atom will do all sorts of things to find electrons that it can use to fill its outermost orbital.

Covalent bonding: Sharing electrons makes atoms happy

So how can an unhappy atom fill up its outermost orbital and achieve chemical nirvana? Here is an imaginary dialog between two hydrogen atoms that meet on the street:

Hydrogen atom 1: I'm so unhappy. I have one lousy electron in my outermost orbital, but I can fit two in that space. If only I could get one more electron.

Hydrogen atom 2: I've got the exact same problem. It's been driving me crazy.

Hydrogen atom 1: Hey! I've got an idea. We both need one more electron -- why don't we share our outermost electrons?!?! That way, we'll each have access to two.

Hydrogen atom 2: Interesting idea. But if we share electrons, that means that everywhere you go, I'll have to go too. We'd be bonded together. I'm not sure I'm ready for that sort of commitment.

Hydrogen atom 1: I understand, but think of how happy we would both be if we were together, each with full electron orbitals.

Hydrogen atom 2: You're right. Let's share electrons.

(The two atoms bond together to form H_2*, and they lived happily ever after. If they were people, we would call the newly joined couple a "family," but the word for a collection of atoms bonded together is a molecule.)*

It is possible for atoms to share electrons in such a way that they can both be happy. When atoms share electrons, chemistry textbooks call this a covalent bond. Since the atoms want to remain in this happy state, it can often be hard to separate them once they have bonded. Astute readers might note that if a hydrogen atom has two electrons (via sharing) but only one proton, it is not electrically neutral. However, the hydrogen is never alone, and you have to look at the electrical neutrality of the entire molecule: the molecule's two total protons balance out the two total electrons.

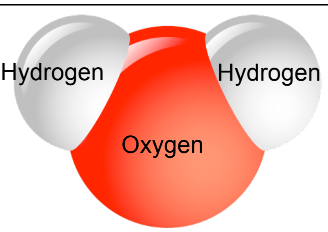

Figure 2. Oxygen shares one electron with the hydgrogen on its left and one with the hygrogen on its right. This relationship keeps the three molecules locked together in this close-knit "Mickey Mouse" shape.
From: http://commons.wikimedia.org/wiki/File:Water_molecule_2.svg

Molecules can (and often do) have many more than two individual atoms sharing. You have probably heard the chemical formula for a slightly more complicated molecule, H_2O (water). Water is a group with one oxygen sharing it's electrons with two different hydrogen atoms. Why would the hydrogens share their electrons with an oxygen atom when they could just share with each other? While that might make them happy, it would leave the oxygen atom all alone and unhappy. It works out that having everybody happy is usually the lowest energy state, so nature prefers to make as many atoms happy as possible. If a two hydrogens have already bonded and are happy when they meet an unhappy oxygen, they may not bond with it right away. You might have to add a little bit of energy to the system to break the hydrogens apart so that all three atoms can bond together happily.

Metals: A special case of covalent bonding

Most bonds are between two atoms. In a molecule like water, the oxygen shares one of its electrons with a hydrogen atom on its left side (one bond) and another electron with a hydrogen atom on its right side (another bond). Certain elements behave a little differently because their electrons are more mobile (not as tightly bound to the nucleus). These atoms can join together and form large groups that all agree to share their electrons. As long as everyone contributes their electrons and has free access to them, the group is able to maintain a utopian existence of happiness. Atoms whose electrons are free enough to participate in this type of bond are called metals. Since electricity is the movement of electrons, it's not surprising that metals are excellent at conducing electricity. Each metal atom is more than happy to let its electron hop over to the next atom, as long as it can share a different electron from another neighbor.

Ionic bonding: It can be better to give than to receive electrons

Sometimes an atom has just one electron in its outermost orbital but can fit as many as eight. The easiest way to reach happiness is just to get rid of that electron, leaving the orbital empty (and all the lower orbitals still happily full). However, the atom can't just ditch the electron – it's negative charge is attracted to the nearby positive charges in the nucleus. The only way it's going to be rid of the extra electron is to find another atom that wants the electron more. Sodium is a common atom with just one electron in its outermost orbital and Chlorine has seven. When the two meet, the sodium atom happily gives its one extra electron to chlorine, which happily accepts it. This exchange of electrons is another type of chemical reaction, and the two atoms are now bonded together. Unlike the covalent bond (where electrons are shared), you'd think that the chlorine would be able to just take the electron and run off alone. However, the chlorine atom has now has a total of 17 positively charged protons and 18 negatively charged electrons -- overall the chlorine has a net charge of negative one. Sodium is in the opposite camp with a net positive charge (one more proton than electrons). Opposite charges attract, so the sodium and chlorine stay bonded together. Good thing that they do, because together they form table salt. We call the type of bond where electrons are exchanged an ionic bond (an ion is an atom that is not electrically neutral).

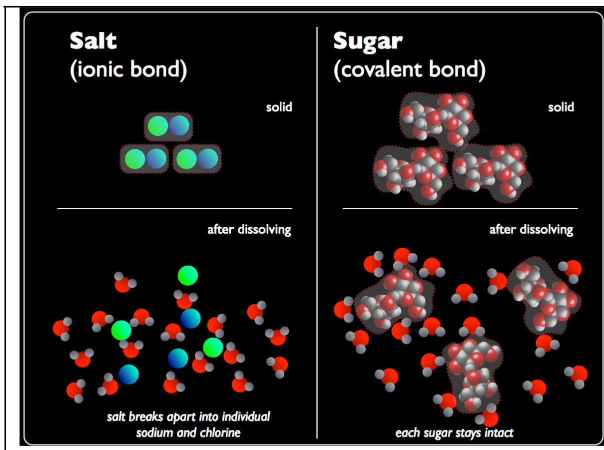

Figure 3. Dissolving ionically and covalently bonded solids in water.

If you take table salt and drop it in water, you can see how its ionic bonds affect its behavior. Salt seems to disappear in water (dissolve), but what actually happens is that the chlorine and sodium are are pulled apart from one another. It turns out that the atoms in water are not quite electrically neutral (water is called "polar" because it acts like it has a "positive" pole and a "negative" pole like Earth has north and south poles). It acts this way because the atoms don't share the electrons exactly equally. The oxygen, which holds the electrons a little closer ends up with a slightly extra negative charge. The positive side of a water molecule competes with the positively charged sodium atoms to attract the negatively charged chlorine atoms. When you drop a grain of salt into water, millions of salt molecules break up into a sea of sodium and chlorine ions that are no longer bonded to one another. Chemistry textbooks use the term aqueous solution to describe any time a molecule dissolves in water (remember *aqu*eous like *aqu*atic). Most ionically bonded molecules will dissolve in polar molecules like water (which are actually pretty rare). Covalent bonds aren't willing to split from their bonded partners because they only get to share electrons. If a covalently bonded molecule does dissolve, the entire molecule will be surrounded by water molecules, but the molecule itself will stay together as a single piece (see Figure 3).

Noble gases: Some atoms are just born that way

Some elements are lucky enough to have the perfect number of electrons and be electrically neutral in their natural, isolated state. That means that they have no need to borrow or share electrons with anybody else and are almost always happy. In fact, any change to their electron configuration at all will make them quite unhappy. This group of lucky atoms are the kings and queens of the atomic world, and chemists like to call them the Noble elements (or the Noble gases, since almost all of them happen to be gas at room temperature). How would you expect such a happy atom to behave when it meets another atom that might need to borrow an electron? Let's watch as argon, a Noble element with all its orbitals full, meets a hydrogen atom.

Hydrogen atom: Brother, can you spare an electron?

Argon atom: Address me by my proper name, you scoundrel. I am *Sir* Argon. Besides, why should I care about you?

Hydrogen atom: I just need one more electron to be happy. Have a little pity.

Argon atom: If I give you one of my electrons, I won't be happy any more. If, heaven forbid, we were to share electrons, I would have too many. You are asking me to sacrifice my happiness to make you happy? That simply doesn't make sense! It doesn't get the world to a lower energy state. What you are asking me to do is like asking one ball to spontaneously roll UP a staircase so that another ball can switch places with it.

Hydrogen atom: So you're saying that you won't bond with me? You're just going to horde your electrons and live out the rest of your life alone?

Argon atom: I won't bond with anybody! I don't need to! I am already happy just by myself.

And so it goes... Noble elements are extremely unlikely to bond with *anything* else and if you combine them with other atoms, *no* chemical reaction will occur. This non-reactivity makes Noble gases really useful. For example, blimps used to use lightweight hydrogen to lift off the ground until the Hindenberg disaster where a hydrogen blimp burst into flames[3] – hydrogen is not a noble gas and reacts easily with oxygen in the air. Instead, the Goodyear blimp and others use Helium, a noble gas that does not easily react with air. Most regular incandescent light bulbs are filled with a mixture that contains argon gas (a noble element). Again, the oxygen in air would easily react with the metal of the thin wire filament that glows to make the light. The reaction would eat away at the filament and light bulbs would wear out quickly without their bulb filled with a noble gas.

The Periodic Table

The periodic table on the wall of every chemistry classroom is not organized to look pretty -- it's organized based on the number of electrons in the outermost orbital (See Figure 3 on the last page). The word "periodic" means that something repeats, and it's called the *periodic* table because the number of electrons in the outermost orbital repeats as you go from one row to the next. In other words, if lithium has exactly one electron in its outermost orbital, then the element directly in the row directly below it on the table, sodium, has the same number of electrons in its outermost orbital (as well as one additional orbital that is completely full; two rows down the element has two more full orbitals, etc.). The number of filled orbitals doesn't affect what an atom needs to do in order to achieve happiness – only the number of electrons in the outermost shell plays a major role. We know that chlorine bonds with sodium to make table salt. It will also bond with lithium and potassium which are directly above and below sodium because they all have one electron that they'd love to get rid of. And if sodium were to encounter fluorine or bromine (which are in the same column as chlorine), you should predict that they will

[3] See http://www.airships.net/hindenburg/disaster or do your own web search for videos of the disaster.

happily bond because, like chlorine, flourine and bromine need exactly one more electron to be happy. Wouldn't it be great if it was this easy to spot compatible relationships in people!

It's not just bonding behavior that repeats, but elements in the same column on the periodic table share other properties as well. For example, gold is known to be a fantastic conductor of electricity and is used in high-end television and stereo equipment as well as the space program for making wires. Since gold is so expensive, maybe you could find an element with similar properties that is cheaper. Sure enough, look two rows up and you'll find copper. Since most of us can't afford gold cables, we use copper instead (or sometimes a thin layer of gold plating on top of copper wires). The same idea works for solar cells, which are typically made from silicon. Directly below it is germanium, and manufacturers were able to make more efficient solar cells when they tried substituting some germanium into the cells. The noble elements from the previous section that share the common behavior of being non-reactive are all located one on top of the other on the column at the right side of the periodic table. When you know how one element in a column behaves, you can bet that others will behave similarly.

Alchemy

Back in the days of castles and kings, one "scientific" pursuit was to try to turn metals like lead into gold. Even though both are metals, lead is common and cheap, but gold has always had great value because it does not rust or corrode easily. Many kings and queens sponsored researchers hoping that they could perfect this process. One theory explored at the time was that you could combine lead with another material and it would undergo a chemical reaction to form gold. The search was on to find that material, which some called the "Philosopher's stone." The quest for this mythical stone became an obsession for many because they hoped that a material able to transform a boring metal like lead into gold might also be able to do other seemingly impossible tasks such as restoring youth or granting immortality. The legend continues in the contemporary book, "Harry Potter and the Philosopher's Stone" (the first book in the series originally carried the "Philosopher's stone" title in the UK, but it was re-titled "Sorcerer's Stone" in the US version) as the fictional wizard tried to keep this magical stone away from his evil nemesis, Voldemort.

Knowing what you know about elements and chemical reactions, is alchemy possible? Is the Philosopher's stone real? On the periodic table, lead has atomic number 82, meaning it has 82 protons. It needs 82 electrons to be electrically neutral. Looking at the periodic table, lead falls in the same column as Carbon with room for four more electrons in its outmost shell. Like all atoms, it desires to be "happy" and have a full outermost shell and will bond with other elements to make that happen. For example, it could form PbO_2 (lead dioxide, which sounds similar to carbon dioxide -- not a surprise since lead and carbon fall in the same column of the periodic table), $PbSO_4$ (lead sulfate, a common ingredient in automobile batteries), or any number of other compounds. All of these will make lead happy, resulting in an electrically neutral molecule with the outermost electron shells filled in all the atoms. However, looking at all of these combinations, they always result in "lead plus something" and never in gold. Gold is a separate element with 79 protons (atomic number 79). No chemical reaction will ever turn an atom with 82 *protons* into an atom with 79 *protons* because chemical reactions are all about exchanging or sharing *electrons*. Because the first 2000 years of alchemists did not understand atoms and chemistry, they wasted their time searching for a Philosopher's stone that cannot exist.

Today's physicists can actually beat a medieval sorcerer because they have succeeded in turning lead into gold in particle accelerators. These multi-billion dollar facilities fire neutrons at atoms at such high speeds that they can make the nucleus unstable. Some protons in the nucleus of a lead atom might escape (or even get so confused that they turn into neutrons). Physicists are able to turn lead into gold by tuning the collision so that it causes three protons to go away. Don't throw away your pick and shovel just yet.... Gold mined out of the ground costs about $35,000 a kilogram. To make gold in a particle accelerator will cost more than a million dollars a shot and produce less than a microgram (10^{-6} kg). [4]

The Secret lives of Electrons

What's really crazy is that individual electrons don't actually take up any space! According to quantum mechanics, the radius of an electron is zero. If you tried to measure them with a ruler, they would never go beyond zero no matter how tiny a ruler you use. It's not that they are really tiny -- it's that they don't take up any space at all. This should not make any sense to you at all because every particle that you are familiar with in every day life has a size. Physicists discovered this less than a hundred years ago, and it caused them to rethink every one of the laws of physics. This newer description of the way the world works is what physicists call "Quantum mechanics." While particles with zero radius may not make sense at first, think about gravity. It occupies no space, but you can definitely sense its effects. An electron acts in somewhat the same way -- even though it doesn't have any size, it still has an electrical charge that has a huge impact on our everyday lives.

Summary

We've seen that protons determine the overall properties of an atom, neutrons keep its nucleus stable, and the quest to obtain the perfect number of electrons drives atoms together in chemical bonds. Electrons move about the nucleus within odd shaped regions called "orbitals," and each orbital only has room for a certain number of electrons. Atoms are "happy" when they have all their outermost electron orbitals completely filled to the maximum capacity because this is the most stable energy state. Atoms are terribly unfaithful, switching bonding partners to join other atoms if it brings the world into an even more stable energy state. Each time atoms bond together or change bonding partners, we call it a chemical reaction. Most chemical reactions result in having all the participating atoms happy with their outermost orbitals filled and the total number of positively charged protons equal to the number of negatively charged electrons. The periodic table is organized so that all the elements in a single column have the same number of electrons in their outermost orbital. They will have similar preferences for chemical bonding partners, making the periodic table the ultimate guide for determining compatible relationships in the chemical world.

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[4] See http://chemistry.about.com/cs/generalchemistry/a/aa050601a.htm and Wikipedia entries for "Alchemy" and "Nuclear Transmutation."

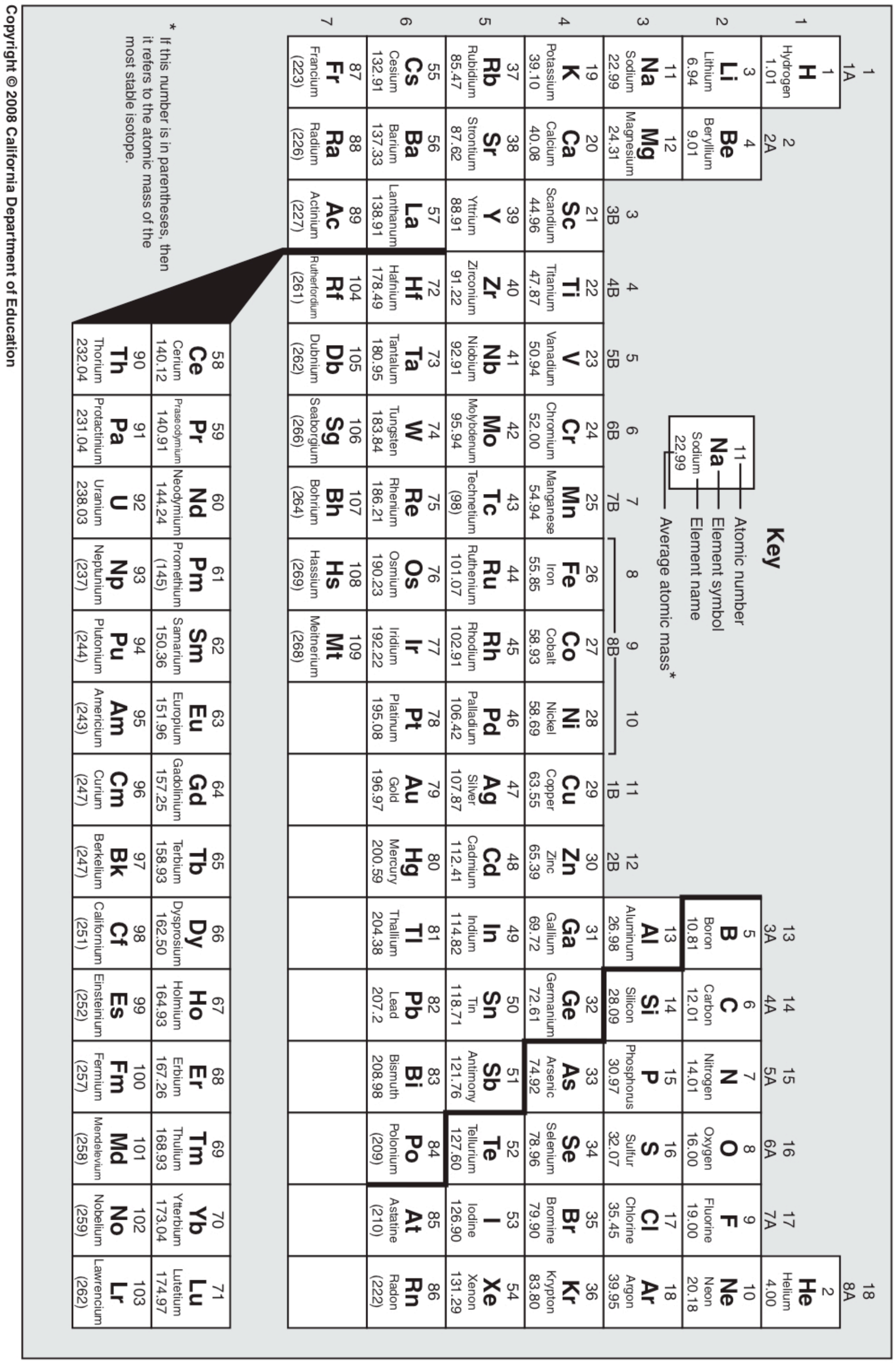


Figure 4. A periodic table of your very own

Potential quiz questions

1. What is the role of the neutron?
    a. Keeping the nucleus stable
    b. Aiding in chemical bonding
    c. Defining the behavior of each element
    d. Neutralizing the atom's electric charge (by providing an equal and opposite charge to balance the proton)
    e. Both a and d
2. How can you change lead into gold?
    a. By bonding lead with the element commonly known as ``the philosopher's stone"
    b. By adding electrons to make it happy
    c. By converting some protons into neutrons
    d. You can never convert one element into another
3. When an atom adds an electron, the electron goes:
    a. Wherever there is room available
    b. Closest to the nucleus
    c. In the outermost orbital
    d. In the space occupied by the last electron that left the atom
4. According to quantum mechanics, what is the radius of the electron?
    a. Zero
    b. So tiny that we have never been able to measure it.
    c. About 1/100,000th the size of the proton
    d. 1/1,000th the width of a human hair.
5. Which of the following describe a chemical reaction? (circle all that apply)
    a. When an atom undergoes beta decay
    b. Old bonds get broken
    c. New bonds form
    d. When an atom changes bonding partners
6. What does it mean for an atom to be electrically neutral?
    a. It has no electrically charged particles
    b. Its total positive charge is equal to its total negative charge
    c. It is made entirely of neutrons
    d. It has no neutrons
7. Which type of chemical bond requires atoms to share electrons somewhat equally?
    a. hydrogen bonds
    b. covalent bonds
    c. ionic bonds
    d. intermolecular bonds
8. Electrons revolve around the nucleus in simple circles like the planets orbit the Sun in our solar system.
    a. True
    b. False
9. What is ``periodic" about the periodic table? All elements in the same BLANK have the same number of BLANK.
    a. row, neutrons
    b. row, electrons
    c. row, electrons in the outermost orbital
    d. column, neutrons
    e. column, electrons
    f. column, electrons in the outermost orbital
10. A molecule is:
    a. Another word for an atom
    b. ``One of the more than one hundred substances that cannot be chemically interconverted or broken down into simpler substances and are primary constituents of matter."
    c. A collection of atoms bonded together
    d. A subatomic particle
11. What is an ion?
    a. When an atom has more protons than neutrons
    b. An atom that is not electrically neutral
    c. An atom that has its outermost orbital filled
12. According to the chapter, what makes an atom ``happy"?
    a. Being electrically neutral
    b. Having the highest amount of energy
    c. Bonding to as many other atoms as possible.
    d. Having the outermost orbital filled with the correct number of electrons
13. What makes bonding between metals different than bonding by other covalent bonds?

a. Electrons are not shared equally in metals
b. A large group of atoms share electrons within the entire group instead of between two atoms.
c. Electrons are given from one atom to another in metals.
d. Electricity can NOT flow through materials with metal bonds.

14. Molecules that are bonded with which type of bond are more likely to break apart when they dissolve in water?
    a. hydrogen bonds
    b. covalent bonds
    c. ionic bonds
    d. intermolecular bonds
15. A chemical bond usually occurs (ignore bonding in metals for this question):
    a. Within a single atom
    b. Between two atoms
    c. Between three or more atoms
    d. All of the above are common.
16. Why isn't an atom always ``happy" when it has the same number of protons as electrons?
    a. Trick question. It is happy.
    b. For some reason, they need to have their outermost electron orbital filled to be in the lowest energy state.
    c. For some reason, they need to have their outermost electron orbital filled to be in the highest energy state.
17. How do noble elements behave?
    a. They freely bond with any atom they want
    b. They rarely bond with other atoms
    c. They easily explode
    d. They hold on to their electrons a little closer and end up with a slightly extra negative charge
18. Lithium bonds with chlorine to make them both happy. Looking at the periodic table, which other elements are likely to bond with Chlorine? (circle all that apply)
    a. The element directly above lithium.
    b. The element directly below lithium.
    c. The element two rows below lithium (same column).
    d. The element directly to the left of lithium
    e. The element directly to the right of lithiu
    f. The element two columns to the right of lithium (same row)
19. What takes up most of the space in an atom?
    a. The nucleus
    b. Protons
    c. Electrons
    d. Neutrons
    e. Nothing. Most of an atom is empty space.
20. The outermost electron orbitals are:
    a. Always full
    b. Never utilized
    c. Filled up before inner orbitals
    d. Important for chemical bonding
21. What happens when you touch something?
    a. Your electrons repel the object's electrons and you feel a force before the two actually touch
    b. Your electrons repel the object's protons and you feel a force before the two actually touch
    c. Your electrons collide with the object's electrons
    d. Your electrons collide with the object's protons
22. In water, oxygen and hydrogen:
    a. Share electrons equally
    b. Hydrogen gives an electron to oxygen
    c. Oxygen gives an electron to hydrogen
    d. Share electrons, but oxygen holds them closer to it

Eight is enough

Until now, we've said only that atoms need the "perfect" number of electrons in their outermost orbital to be happy. How many is that? Nature has made this relatively convenient for us and the perfect number is…**eight** (though hydrogen and helium are so small that they are exceptions and only like to have two electrons).

To explain why it's eight, we'd need to understand a lot more about quantum mechanics. We are not going to do that, but it turns out that you don't need to understand why to understand "why eight is important." As early as the 1860's, scientists were starting to realize that there were eight main groups of elements that behaved similarly, though they had no idea why. The electron wouldn't be discovered for another 30 years, and the sophisticated ideas of quantum mechanics were three quarters of a century away. But they still recognized the importance of 8 and organized the periodic table around it. At the top of each column in your periodic table (Figure 4) are two small numbers – one just goes from 1-18 for each column, but below that are little numbers grouped into categories A and B. From 1A to 8A and 1B to 8B (the B category refers to metals, which we saw above engage in a slightly different sort of bond than all the other elements).

We now know that the numbers above each column refer to the number of electrons in the outermost orbital when the atom is by itself (and electrically neutral – while atoms prefer to be electrically neutral, they are not always when you find them in nature). Oxygen is in column 6A, so it must have six electrons in its outermost shell. Being number 16 on the periodic table, it must have 16 protons and an equal number of electrons if it is electrically neutral. (We've already said that six of them are in the outermost shell, that means 10 electrons must be located in the inner orbitals, which are less important for chemical bonding.) This rule does *not* work well for the metals in columns 1B-8B on our table, so you'll need to learn more chemistry to find out how many valence electrons they have in their outermost orbital.

If eight is the perfect number of outermost electrons and oxygen has six, how many does it need to beg, borrow, or steal in order to be happy? (TWO). In fact, all the elements in column 6A need two more electrons to be happy. Where would you find an atom with two extra electrons around? All the elements in column 2A have only two electrons in their outmost orbitals. If they get rid of those electrons, they can empty out an entire orbital.

Electron dot notation

Chemists have developed a convenient way to help you visualize the outermost orbital of electrons, with its eight available spots called "dot notation." You surround an element's one or two letter symbol with eight circles to represent the eight possible spaces in the outermost electron orbital. If the atom has an electron, you fill the circle in. If an atom has seven electrons in its outermost orbital, you fill in seven circles and leave the eighth empty. You can fill them in using any order you like. Here are some examples:

(Notice the odd-ball on the end – Hydrogen, H, only has two available spots in its outermost electron orbital.)

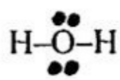
The idea is that you can quickly see who will be a good partner for chemical bonding. We'll work a lot with salt in class because it is a simple chemical formula: NaCl. Here is the dot structure for each of the two molecules by themselves:

Neither of these atoms is "happy" yet. One book I read[5] describes the electron orbitals as like a parking lot and each electron like a car. Parking lots like to be either completely full (with a car in every space), or completely empty (so that they can put up the gate and give the parking attendant the day off). Using this analogy, you can quickly see that moving the one car from sodium to chlorine will allow one parking lot (outermost electron orbital) to close (be empty) and the other to be completely full. Happiness for all!

Let's try another example:

Hydrogen has one empty slot, but oxygen has two. Having oxygen bond with one atom of hydrogen will still leave one empty slot in the oxygen's diagram. That's how you know it will want to form bonds with TWO hydrogen atoms (forming H_2O!).

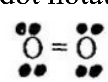
We often represent the chemical bond with a dash. Instead of drawing two dots, you draw the dash. You can remember that a dash has two ends, with each end representing one electron.



Will the bond be ionic or covalent? A tough question! It's not possible to tell just by looking at the dot structures. You need to know something about each particular element involved. Some atoms like to hold on to their electrons and are only willing to share them. Others are willing to loan them on a semi-permanent basis. If you want to be able to predict whether a bond will be ionic or covalent, you'll have to become a chemistry major and learn more about how atoms work!

Let's look at another example:

Each oxygen needs two electrons. If there is no hydrogen around, these oxygens could team up. They would need to share TWO pairs of electrons, which is allowed. We call this a "double bond" and represent it in dot notation using:



[5] Trefil, James and Hazen, R. M., 2009, *The Sciences; an integrated approach* (5E), Wiley: Hoboken, NJ, 260 pp.