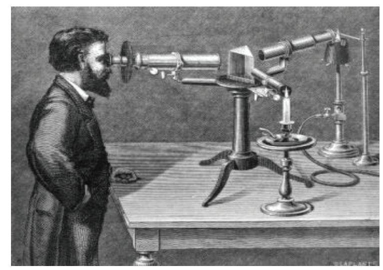
CHAPTER 6: THE NOBLE GASES AND THE NON-METALS

Think back to our Periodic Kingdom fairy tale. Do you remember the description of the Noble Gas family? They were the most peaceful rulers a kingdom could hope for. Nothing ever upset them. The real science behind this part of the story is that the noble gases are the only elements on the Table that have the exact number of electrons they want in their outer shells. Of course, using words like “peaceful” and “happy” to describe something that isn’t alive is a little silly, but it does help us remember the real science.

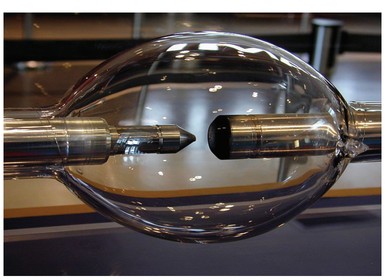
A chemist would say that the noble gases are “inert,” which means they don’t react with anything. An atom of helium doesn’t want to give or get any electrons because its outer shell is full. Therefore, it will not interact with the atoms around it. Because it is inert, helium won’t react with the atoms in your body, which is why it isn’t dangerous to take a breath of it in order to talk funny.



A scientist of the 1800s using a spectrometer

Helium’s spectral pattern

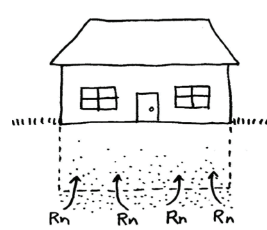
Helium was named after the Greek god of the sun, “Helios,” because the sun was the first place that helium was discovered. The discovery was made in the year 1868 using a machine called a **spectroscope**. If you look at a light source through the spectroscope you will see colored lines. Each element has a unique pattern of lines. Sodium’s pattern is very simple and consists of basically two yellow lines. (To see the pattern you have to heat or burn the sodium so that it makes light.) Looking at the sun is a bit risky, as it can cause eye damage. The discoverers of helium looked at the sun during an eclipse, when the light was reduced and therefore less dangerous to look at. They saw sodium’s two yellow lines, plus many others that they recognized, but they also saw a new pattern they didn’t recognize. They understood that what they were seeing was probably a new element and they immediately named it helium, thinking it was a special element found only in the sun. Then, in 1903, large amounts of helium were found mixed in with natural gas deposits. Later, it was also found mixed in with uranium ore. Helium was definitely part of the earth’s natural chemistry, not just the sun’s. (Later, it was discovered that helium is a by-product of radioactive decay.)



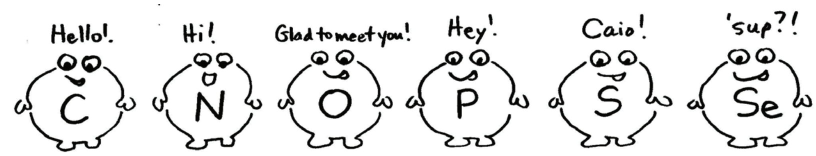
Attribution: Atlant, on Wikipedia “xenon”

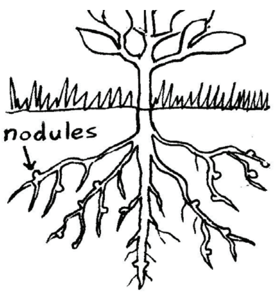
Because the noble gases are inert, they are ideal for use in light bulbs. They will not ignite or explode and are safe even when exposed to electrical currents. Neon is (obviously) used in neon lights, argon is used in ordinary bulbs, krypton is found in fluorescent bulbs and camera flashes, and xenon is put into ultraviolet lamps, camera flashes, and lighthouse bulbs. The xenon bulb shown here is used to project IMAX films, which require a very bright light source. Helium, neon and argon are also found in the most common types of lasers.

You may have heard that radon causes lung cancer. This noble gas is inert, just like all the others, so why does it cause problems? The problem with radon is not its electrons, but its nucleus. Radon is radioactive, which means its nucleus is throwing out harmful particles. Radon occurs naturally in the earth, especially in areas that have lots of uranium. Mostly, radon just goes up into the air and gets lost in the atmosphere. It only causes problems when a whole lot of it seeps up into the basement of a building or into a mine shaft.

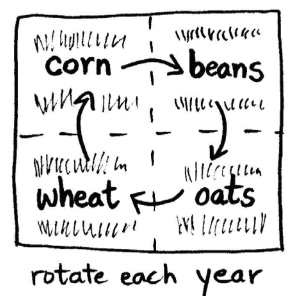


We already talked about one section of non-metals, the halogens. The other members of the non-metal group are carbon, nitrogen, oxygen, phosphorus, sulfur, and selenium. Some chemists also include boron in the non-metal group. We could also include hydrogen as a non-metal if we wanted to. Hydrogen is sort of a group unto itself, but it is found connected to carbon and oxygen so often that we could legitimately think of it as a non-metal.





Nitrogen makes up almost 80% of the air we breathe. Nitrogen gas is made of two atoms of nitrogen bonded to each other to form N_2. The nitrogen we breathe doesn't do anything but take up space in our lungs. It's the oxygen that we need from the air. We do need nitrogen in our bodies, though, as it is an essential ingredient in proteins. The nitrogen atoms found in proteins come from the food we eat, however, not the air we breathe. Plants have a similar situation. They need nitrogen to make chlorophyll, but they can't get the nitrogen out of the air. Nitrogen is all around them, but the plants can't use it. For a plant to be able to take in nitrogen, the nitrogen atoms must be attached to molecules in the soil. Fortunately, there are bacteria in the soil that are capable of taking nitrogen out of the air and putting it into a form that plants can use. They are called "nitrogen-fixing" bacteria. You can find these bacteria growing in colonies on the roots of certain plants. The bacteria colony will look like a little bump about the size of the head of a pin. These bacteria prefer to grow on the roots of beans, peas, peanuts, soybeans and clover. Ancient farmers knew that these plants enriched the soil, but they did not know why. They rotated their crops each year, so that each field would get a turn having a bean crop in it. The beans would restore the nitrogen to the soil. In modern times, farmers just put nitrogen fertilizer on their fields.

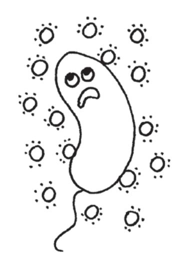


If you have a super-powerful refrigeration unit, and can cool nitrogen down to several hundred degrees below zero, it turns into a liquid—a very cold liquid, so cold that it can freeze things instantly. As soon as it is exposed to air or water, it boils and evaporates, returning to its gaseous state, returning to the air from whence it came.

Activity 6.1 Fun with liquid nitrogen

Liquid nitrogen isn't easy to get. It takes a special (expensive) refrigeration unit to get the temperature down to hundreds of degrees below zero. Fortunately, some folks who do have access to liquid nitrogen have filmed their demonstrations and posted them on the Internet so we can see them. Go to YouTube.com/TheBasementWorkshop and you'll find some videos showing liquid nitrogen experiments.

Oxygen makes up about 20% of the air we breathe. Just like nitrogen, oxygen goes around in pairs (O_2). A single oxygen atom is a very unhappy atom because it has two empty electron slots in its outer shell. One oxygen atom by itself is very dangerous. We've learned to use this to our advantage, though, when we want to get rid of germs. Bleach, NaClO, has that single oxygen atom hanging on the end of the NaCl, and it can fall off very easily. When the oxygen atom falls off, it goes about looking for electrons. It will steal electrons from anything nearby, hopefully a germ that we want to kill anyway. A whole bunch of single oxygens can wreck a bacteria's molecules so badly that it dies.

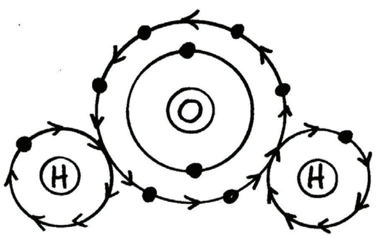


"Help! I'm surrounded by single oxygens!"

When two oxygen atoms pair up as O_2, the electron math doesn't work out perfectly. If each oxygen atom wants to get 2 electrons, then how can they be happy together? They work out an arrangement where they each share one of their electron pairs. Electrons move so fast that they can almost be in two places at the same time. Almost. So for a split second, one oxygen will have its own 6 electrons plus the 2 it is borrowing, to make 8 in the outer shell. For that split second it is happy. Then it must return the favor and share a pair with the other atom. This would mean that for a split second it would only have 4. But before it can get really unhappy about that, it's suddenly time to receive again, and it finds itself with 8 for another split second. This back and forth sharing happens so fast that the atoms feel like they have 8. Or at least they feel like they have 8 just often enough to prevent them from splitting up into singles. However, the fact that they are not completely content with the situation is also what makes them so useful to living things. They can be split up and used for many biological processes. Oxygen is also necessary for the energy-releasing process of combustion (burning).

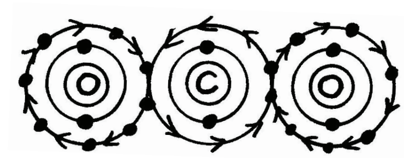
Another place oxygen is found is as a main ingredient in many minerals. Oxygen bonds with silicon to make SiO_2, sand. Both glass and quartz crystals are made of SiO_2. The minerals hematite (Fe_2O_3) and magnetite (Fe_3O_4) are commonly found in the earth's crust. Even ice, which is frozen H_2O, can be classified as an oxide mineral.


A hematite carving

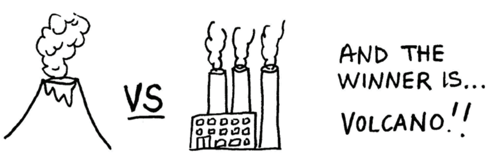


Speaking of H_2O, let's take a look at how these atoms stay together. We won't see an ionic bond here. Ionic bonds are formed only by the elements on the far sides of the table. An atom on the left side pairs up with an atom on the far right side, such as sodium and chlorine. Oxygen does not make ionic bonds. Non-metal atoms form a type of bond called covalent. In **covalent bonds**, electrons are actually shared, not given away. We won't see any electrically unbalanced atoms here. The atoms match themselves up so that they can all share their electrons. For example, oxygen has 6 electrons in its outer shell and hydrogen has 1. Two hydrogens can get together with one oxygen and all three of them together have a total of 8 electrons. The 8 electrons circulate around (at lightning speed) and make sure all the atoms are happy. (Of course, hydrogen is very small and doesn't want 8. It only wants 2.)

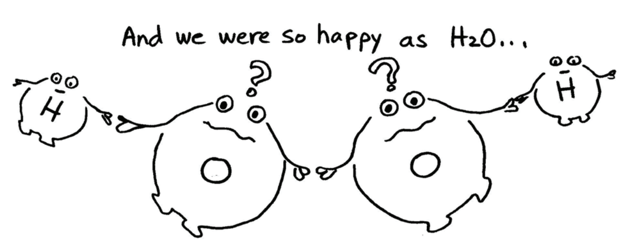
Another example of covalent bonding is carbon dioxide. One carbon atom gets together with two oxygen atoms. The oxygens would like to gain 2, and the carbon doesn't mind sharing its 4. As electrons move very quickly, the atoms can manage to share the 8's.



Sulfur also has 4 electrons in its outer shell. Sulfur can bond with two oxygens, just like carbon can. SO_2 is called sulfur dioxide. (You may be catching on by now that "di" means "two.") Sulfur dioxide is a poisonous gas. When it is released into the air (often by coal-burning factories), it causes air pollution and acid rain. It's not just humans that make sulfur dioxide, though. Volcanoes make far more of it than any factory does.



Now here is a very strange covalent molecule: H_2O_2, hydrogen peroxide. This is the stuff that looks like water but is used for first aid, to clean cuts and scrapes on your skin. Let's do an electron count. The hydrogens each have 1 electron, and the oxygens each have 6. That's 6+6+1+1=14. Whoa! How can that be?



Hydrogen peroxide is water with an extra oxygen stuck on. Water is perfectly content the way it is. Why would it want another oxygen stuck onto it? This is another case of an oxygen atom that can easily fall off its molecule and become a dangerous single oxygen. If you want to kill germs, single oxygens can really help!

Phosphorus was first discovered in the year 1669 when a chemist was boiling a batch of... urine. No kidding, he collected hundreds of gallons of pee and was going to boil it until it turned into gold. Well, urine is yellow, gold is yellow—could be a connection there, you have to just try it and see. What he got was far more amazing than gold. It looked like a disgusting lump of yuck (and it smelled terrible) but when you heated it, it glowed fantastically with a brilliant white light. Back in the 1600s they had never seen a light bulb, so glowing phosphorus must have seemed almost magical. He had discovered one of phophorus' more interesting qualities. The name phosphorus means "light-bearer."

Pure phosphorus can be either white or red. In white phosphorus you find 4 atoms binding together to cope with their three empty electron slots. Eventually, white phosphorus turns into red phosphorus as those foursomes split apart. You've seen red phosphorus on the tips of matches. Match heads also contain sulfur, another non-metal.

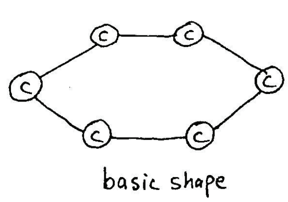
Phosphorus is also involved in energetic tasks in living cells. When combined with oxygen, it's the P in the ATP—a molecule that acts like a rechargeable battery. Phosphorus is necessary in other biological process, also, so it is an element essential to life.

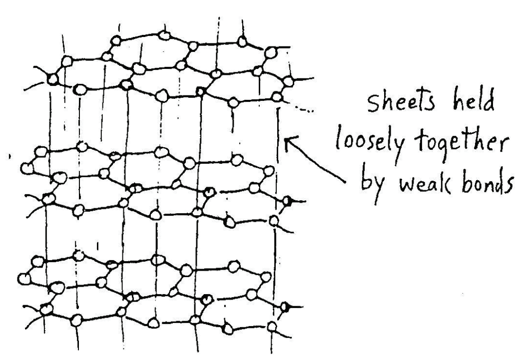
White phosphorus in a jar of water

Carbon is the most amazing atom in the non-metal group. Because it has a valence of +4 or -4, it can bond with itself or with other atoms in all kinds of ways. When carbon bonds with itself, it can make something as humble and inexpensive as graphite (the "lead" in pencils) or as valuable as a diamond. It may be hard to believe, but graphite and diamonds both have the same chemical recipe: just carbon. How, then, can they be so different?

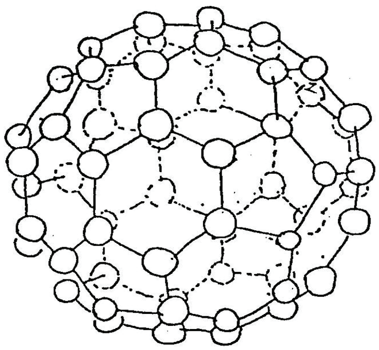
To discover the answer we must look at how the carbons are bonded to each other. In the case of diamond, the basic geometrical shape looks like a pyramid. When millions upon millions of these molecules are bonded together like this, we get a diamond. The bonds in this shape are very strong, which is what makes diamonds so hard.

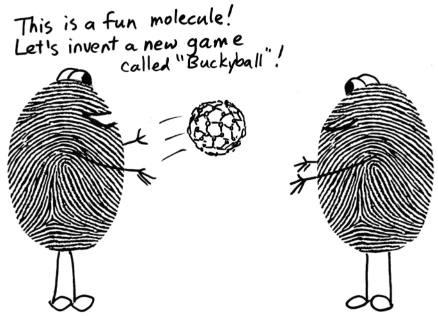
Another shape that carbon can bond into is a six-sided hexagon. Graphite is layer upon layer of flat sheets of connected hexagons. The sheets are only loosely held together, and can slide back and forth. This is why pencils rub off onto paper, and why graphite can be used as a dry lubricant. (Graphite from a pencil can be rubbed onto the bottom of wooden dresser drawers to make them slide in and out more easily.) Technically, if you could squeeze the graphite in your pencil hard enough to make the carbons change their geometry from hexagons into pyramids, you could make a diamond.





The most fantastic shape carbon can make looks exactly like a soccer ball. Sixty carbons can join together to form a sphere made of hexagons and pentagons. Since this shape looks a bit like the geodesic domes used in architecture, it was named after an architect famous for designing dome structures, Buckminster Fuller. Chemists decided to name this molecule "buckminsterfullerene," or "bucky ball" for short.





Carbon is the central atom in all organic molecules. We call molecules "organic" if they are based on carbon. Some types of organic molecules are found in plants, animals and microorganisms. It is the "backbone" of DNA, proteins, sugars and starches. Other kinds of organic molecules aren't found in living things. The molecules that plastic is made of, for example, are called organic because they contain long chains of carbon atoms. Gasoline and other petroleum products are also carbon-based and are therefore classified as organic. (If you'd like to learn more about all the amazing things carbon can do, there's a sequel to this book called Carbon Chemistry.)

Pure sulfur is a yellow solid.

Garlic gets it smell from the sulfur compounds it contains.

Sulfur is right under oxygen on the Periodic Table. This means it also has 6 electrons in its outer shell, and would like to gain 2 more to make 8. It will, therefore, have some chemical similarities to oxygen. However, sulfur atoms are larger than oxygen atoms, having an atomic mass (weight) double that of oxygen. Larger atoms are less likely to be gases. (Krypton, xenon and radon are curious exceptions to this rule.) Pure sulfur is found as a yellow solid and has a strong odor. That's one of sulfur's characteristics—it smells. Sulfur is found in many organic molecules in both plants and animals. It's the key element in the stink of skunks and garlic. When eggs go rotten, they produce hydrogen sulfide, H_2S, which smells bad in a sulfur-ish way.

Sulfur is part of several amino acids (the stuff that proteins are made of). Its presence in hair proteins makes hair waterproof. Sulfur can allow molecules to make "cross-bridges" which makes them tougher. It can be added to rubber to keep it from melting in high temperatures and cracking in low temperatures.

Selenium is right under sulfur on the table, which means it has the same number of electrons in its outer shell. Since selenium has the same valency as sulfur, it is sometimes found in minerals that usually contain sulfur, with selenium taking the place of sulfur. The metal atoms in these minerals are happy with either sulfur or selenium; it doesn't make a big difference to them. Both S and Se want to make 2 bonds, and that's the most important issue to the metal atoms. They'll bond with either one.

Selenium's name comes from the Greek word for the moon, "selene." Selenium doesn't have any features of the moon. It seems that the discoverer of selenium noticed its striking similarities to the element tellurium, right underneath it on the Table. He thought that since tellurium was named after the earth, perhaps the "earth element" should have a "moon element" nearby. Or so the story goes.

Selenium is named after the moon.

Selenium is found in some key molecules in our bodies, but it is not as abundant as oxygen and sulfur. Some people take selenium supplements because selenium is said to be able to help clean up "free radicals" in the body. Free radicals are dangerous fragments of molecules. Selenium used to be used quite a bit in the electronics industry, but now silicon has taken over. Selenium is still used by the glass making industry, and it is also a key ingredient in solar cells.

The halogens (fluorine, chlorine, bromine, iodine and astatine) are a subset of the non-metal group. We can think of them as non-metals, or as the salt-making halogens. Both are correct.

Some chemists like to put boron, silicon, arsenic and tellurium into the non-metal group, as well. This causes a lot of confusion for chemistry students. If you do a search on the Internet for Periodic Tables, you will find that some tables color code these elements to be in the non-metal group. Other tables will have them color coded to match the metal group along with aluminum and tin. And still others will split the difference and put them into their own group called the semi-metals. Who should we believe? In the end, it doesn't matter too much how they are classified because the elements don't care and classification doesn't change them in any way. They are what they are no matter what we call them. Perhaps the most important lesson to learn here is that scientists don't always agree!

Activity 6.2 Watch a demonstration that uses noble gases

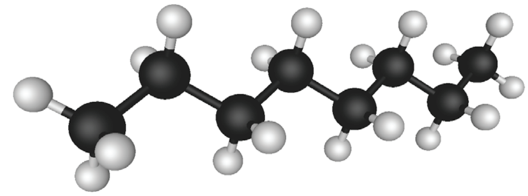
Except for helium, noble gases are not items we can just pick up at the store. Therefore, we have to rely on generous scientists who take the time to post their noble gas demonstrations on YouTube. There should be one or more posted for you at the Elements playlist. One of them shows six balloons, each one filled with a different noble gas. What will happen when the demonstrator lets them go? Helium is easy to predict, but what about xenon?

If you like silly animated cartoons, there is also a cartoon music video made by a student (perhaps not too much older than yourself) with funny rhymes and pictures about the noble gases.

Activity 6.3 A famous silly song about the elements

A number of years ago, an entertainer named Tom Lehrer wrote and performed "The Elements Song." The lyrics of the song are simply the names of the elements, rearranged so that they rhyme. (This means they are not in order, so you can't use this song to memorize the Table.) There are several versions of this song posted on The Elements playlist YouTube.com/TheBasementWorkshop. One version is a historical film (in black and white) of Mr. Lehrer performing his song for an audience. Another version provides a nice picture of each element as it is named, and a third version has the song slowed down so you have a better chance of being able to sing along.

Activity 6.4 A puzzle about carbon-based molecules



There's nothing like carbon when you want to form bonds. Carbon bonds in more ways and with more elements than anything else on the Periodic Table. It's the "nice guy" of the elements. You could imagine it being willing to shake hands and form friendships with just about anyone. It also likes to link up with other carbons and make long chains. Long chains of carbon atoms that have hydrogens all along the sides are called hydrocarbons (duh). Small hydrocarbon chains make things like natural gas (methane) and gasoline (petroleum). Medium-sized chains make things like wax, paraffin, and tar. Really long chains are found in plastics. Hydrocarbon chains can have other atoms attached to them, too, besides hydrogens. When chlorine joins the chain, we get PVC plastic (polyvinyl chloride) that is used for plumbing pipes.

Carbon also forms the "backbone" of many of the molecules in your body. Carbon atoms are the foundation, or anchoring points, for the other atoms in the molecules. Attached to the carbons, you'll find many of our non-metal friends: hydrogen, oxygen, nitrogen, phosphorus, and sulfur. In specialized bio molecules, you might find some metal atoms such as iron (in hemoglobin that carries oxygen) or zinc (in molecules that control DNA). Carbon and its non-metal friends can be combined in almost endless ways, forming the vast number of biological molecules that make living things.

In this puzzle, write the letter symbol that goes with the atomic number written under each blank. For example, for the number 6 you would write the letter "C" for carbon. The letters will spell out the name of a substance that has carbon-based molecules. (Some letters don't appear by themselves on the table, so we just wrote them in.)

1) ___ ___ ___ ___ ___
15 57 16 22 6

2) ___ ___ ___ ___ ___
31 16 8 3 10

3) ___ ___ ___ ___
59 8 91 10

4) ___ ___ ___ ___ T
33 15 1 13

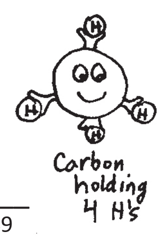
5) ___ ___ ___ L
13 27 67

6) ___ ___ ___ ___ ___ ___ ___ L
5 92 6 19 39 5 13

7) ___ ___ ___ E___ ___
20 9 9 53 10

8) ___ ___ ___ ___ ___ D
95 49 8 89 53
(building block of proteins)

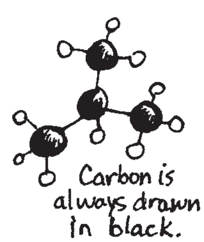
9) ___ ___ ___
9 85 16
(a type of wax)



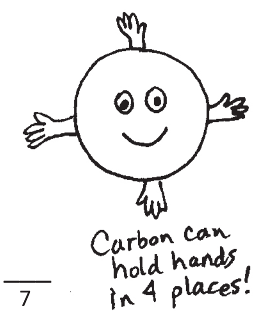
10) ___ ___ ___ ___ ___
91 88 9 9 49

11) ___ L ___ ___ ___ R
84 39 99 52

12) G ___ ___ ___
71 27 34
(a sugar)



13) ___ ___
105 77



14) G ___ ___ ___
71 52 7

15) ___ ___ L ___ ___
7 39 8 7

16) ___ ___ ___ ___ ___ ___ ___
18 22 9 53 6 53 13

___ ___ ___ ___ RS
9 57 23 8

17) ___ ___ ___T ___ ___ ___R
15 57 7 9 53 4

> TRIVA QUIZ: What letter of the alphabet does does not appear in any of the symbols on the Periodic Table?

Activity 6.5 Practice makes perfect!

Here is a review activity to jog your memory about what you learned in past chapters.

1) If an atom could be enlarged to be the size of a sports stadium and the nucleus was sitting in the middle of the field, about how big would the nucleus be?
a) the size of a watermelon b) the size of a marble c) the size of a car d) the size of an elephant

2) What do you call an atom that has more electrons that protons, or more protons than electrons?
a) an alkali b) an isotope c) radioactive d) an ion e) covalent

3) What is the valence number for oxygen? a) -2 b) -1 c) 0 d) +1 e) +2

4) What "family group" on the Periodic Table is perfectly happy? _______________________

5) What "family group" has only 1 electron in their outer shells? ________________

6) What "family group" has 7 electrons in their outer shells? ___________________

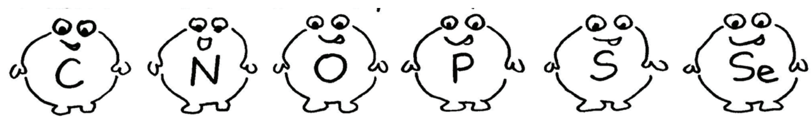
7) Which element causes the stink in skunks and garlic? ___________________

8) Which element can form a circle called a bucky ball? __________________

9) Which element is taken from the air by bacteria and put into the soil? ___________________

10) Which element was first discovered in the sun? _______________

Match the formulas with their common names. (Word bank: plaster, sand, Teflon, salt, bleach)
11) SiO_2 _________
12) NaCl _________
13) NaClO __________
14) C_2F_4 __________
15) $CaSO_4$ ______________



"We know all the answers but we're not not telling!"

16) An atom of magnesium is most likely to bond with: a) N b) C c) O d) F e) Ne

17) An atom of potassium is most likely to bond with: a) Na b) B c) Ca d) Mg e) Cl

18) The atomic number is the number of ___________ that an atom has.

19) Which of these things is NOT made of carbon? a) diamonds b) graphite c) coal d) glass

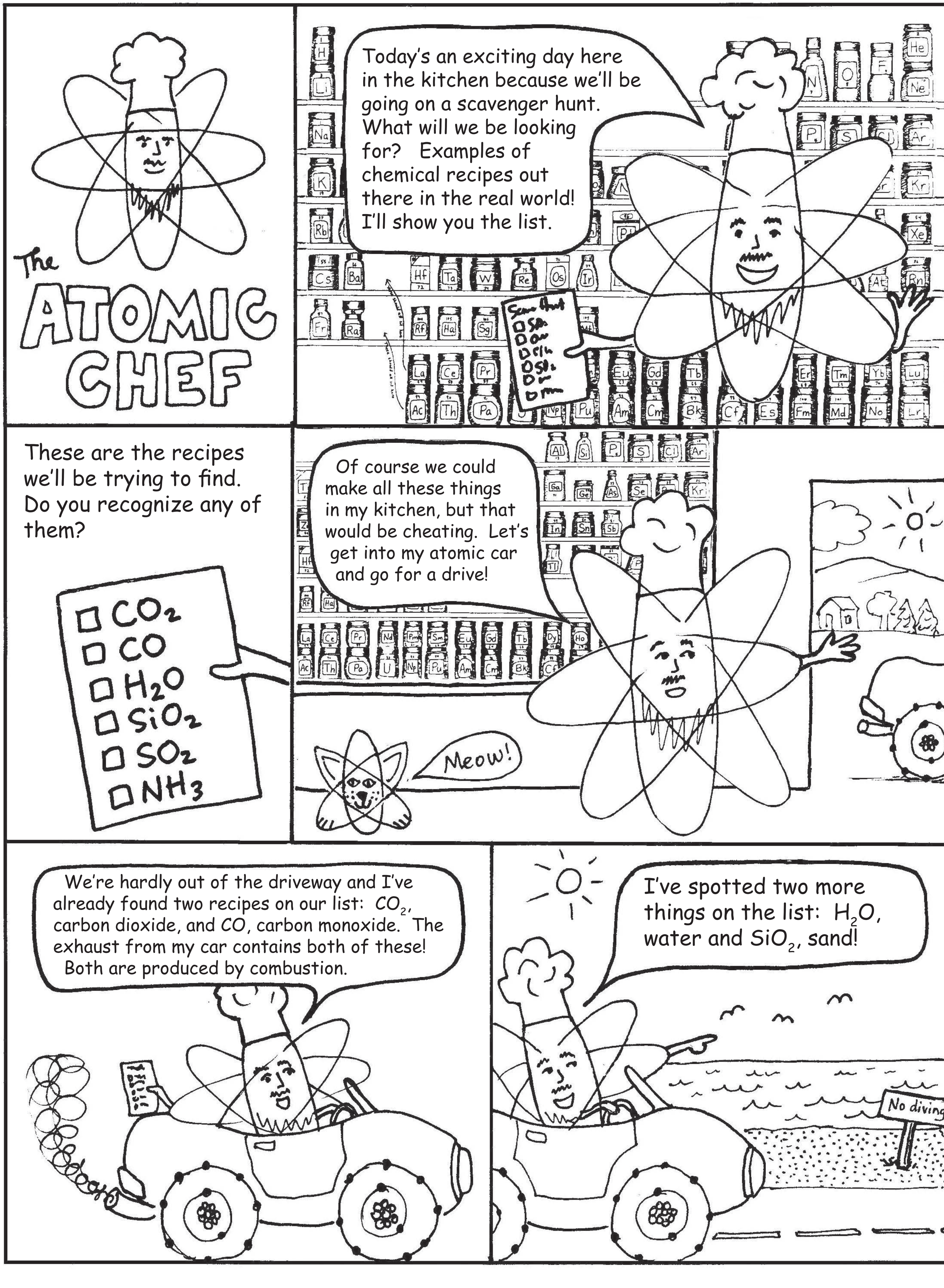
20) Which of these statements is NOT true about electrons?
a) Electrons don't like to be close to each other. b) Electrons like to "work" in pairs.
c) Electrons have a positive electrical charge. d) Electrons weigh almost nothing.

<u>BONUS QUESTIONS</u> (a little harder)

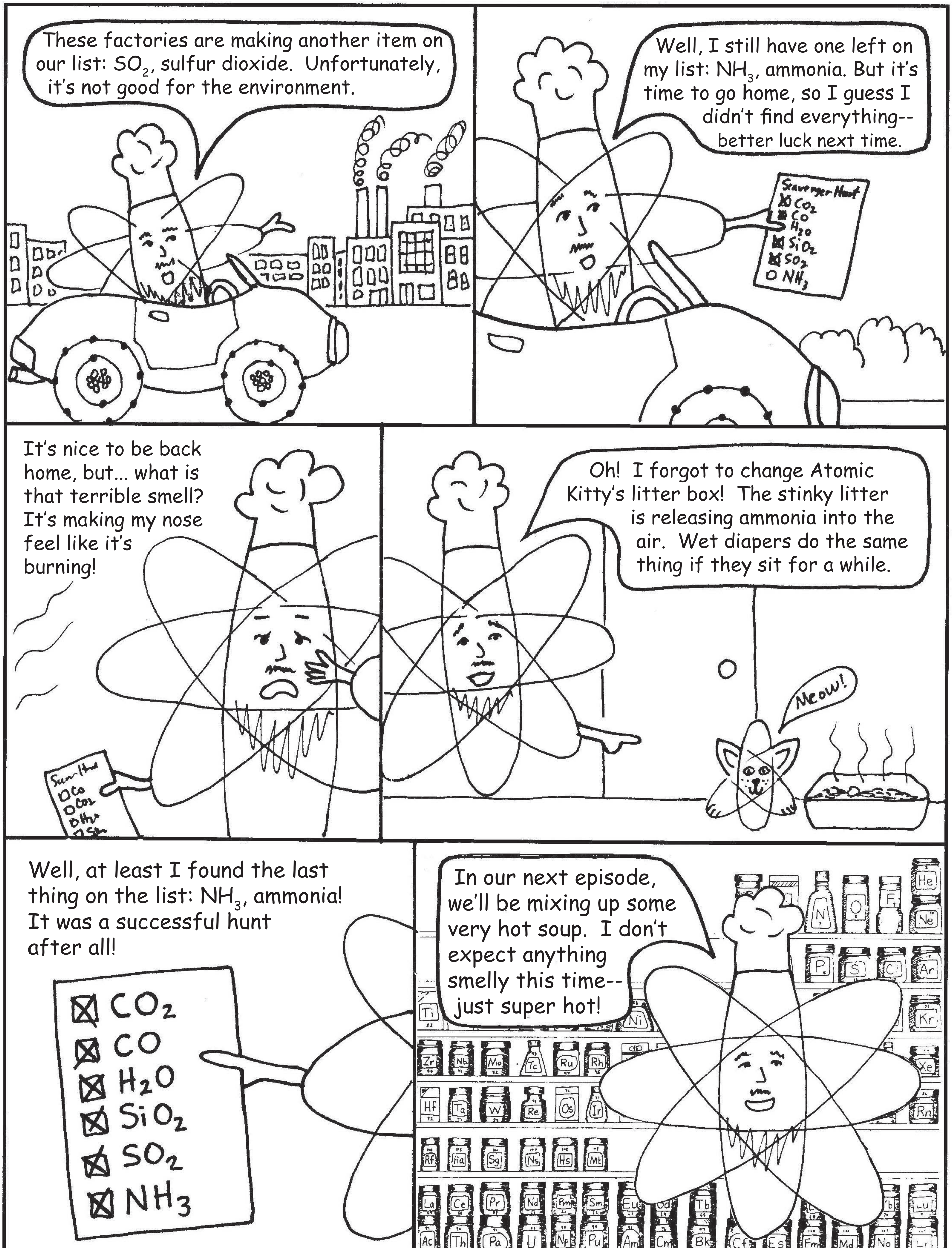
1) What atom is this? $1s^2 2s^2 2p^6 3s^2 3p^4$? ____________

2) Protons and neutrons have a mass (weight) of 1 amu (atomic mass unit). So the mass of an atom is equal to the number of protons plus the number of neutrons. If an atom of uranium has a mass of 238 and uranium's atomic number is 92, then how many neutrons does this atom have? ______

3) When you see a number outside of the parentheses, like the 2 in this formula: $(OH)_2$, that means you have two of whatever is inside of those parentheses, in this case 2 (OH)'s. So you have 2 O's and 2 H's. How many O's (oxygens) are in this mineral? _____ $Ca_{10}Mg_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$



The ATOMIC CHEF
Today's an exciting day here in the kitchen because we'll be going on a scavenger hunt. What will we be looking for? Examples of chemical recipes out there in the real world! I'll show you the list.
These are the recipes we'll be trying to find. Do you recognize any of them?
CO_2
CO
H_2O
SiO_2
SO_2
NH_3
Of course we could make all these things in my kitchen, but that would be cheating. Let's get into my atomic car and go for a drive!
Meow!
We're hardly out of the driveway and I've already found two recipes on our list: CO_2, carbon dioxide, and CO, carbon monoxide. The exhaust from my car contains both of these! Both are produced by combustion.
I've spotted two more things on the list: H_2O, water and SiO_2, sand!
No diving


These factories are making another item on our list: SO_2, sulfur dioxide. Unfortunately, it's not good for the environment.
Well, I still have one left on my list: NH_3, ammonia. But it's time to go home, so I guess I didn't find everything-- better luck next time.
It's nice to be back home, but... what is that terrible smell? It's making my nose feel like it's burning!
Oh! I forgot to change Atomic Kitty's litter box! The stinky litter is releasing ammonia into the air. Wet diapers do the same thing if they sit for a while.
Meow!
Well, at least I found the last thing on the list: NH_3, ammonia! It was a successful hunt after all!
CO_2
CO
H_2O
SiO_2
SO_2
NH_3
In our next episode, we'll be mixing up some very hot soup. I don't expect anything smelly this time-- just super hot!