College Guild
PO Box 696, Brunswick ME 04011

SCIENCE SAMPLER
~ Chemistry ~
Unit 3 of 5

In unit 1, we learned that all matter and space jumped into existence in a "Big Bang." In unit 2, we learned that all matter is composed of atoms, which consist of the fundamental particles: protons, neutrons, and electrons. In this unit, we will learn about *chemistry*: the science of how atoms combine to form all the substances in the universe.

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Part 1. Before Chemistry

Chemistry is the study of the fundamental nature of *substances* (basically any kind of identifiable stuff) and how these substances combine or *react* to form new substances. Before there was chemistry there was superstition, guesswork, and trial and error. Whereas early astronomers could study the planets and stars by just looking up at the night sky, early chemists could not see what was happening at the *microscopic* scale, where reactions take place.

Prescientific people knew how to distill water, find precious stones and crystals, create fireworks, and even purify metals and create *alloys* (mixtures of metals), such as bronze.

But they also tried to create gold from other metals (not possible!), develop potions and other cures (which they experimented with on their patients), and find or manufacture the fabled philosopher's stone, which, it was said, would give one everlasting life. These efforts were called *alchemy*. See the figure to the right.[1]

Medieval Alchemy Workshop

While alchemists were often very skilled and developed many techniques that would later be useful to chemists, we consider alchemy to have been a *pseudoscience* (pseudo = false), replaced by the science of chemistry.

1. **What grand-scale discovery could you make that would benefit our planet and its inhabitants? What microscopic discovery?**

2. **Prescientific people used meteoric iron, a rare alloy of iron and nickel that really did originate from space. What do you think they used it for?**

3. **Give some other examples of pseudoscience.**

Part 2. The Elements

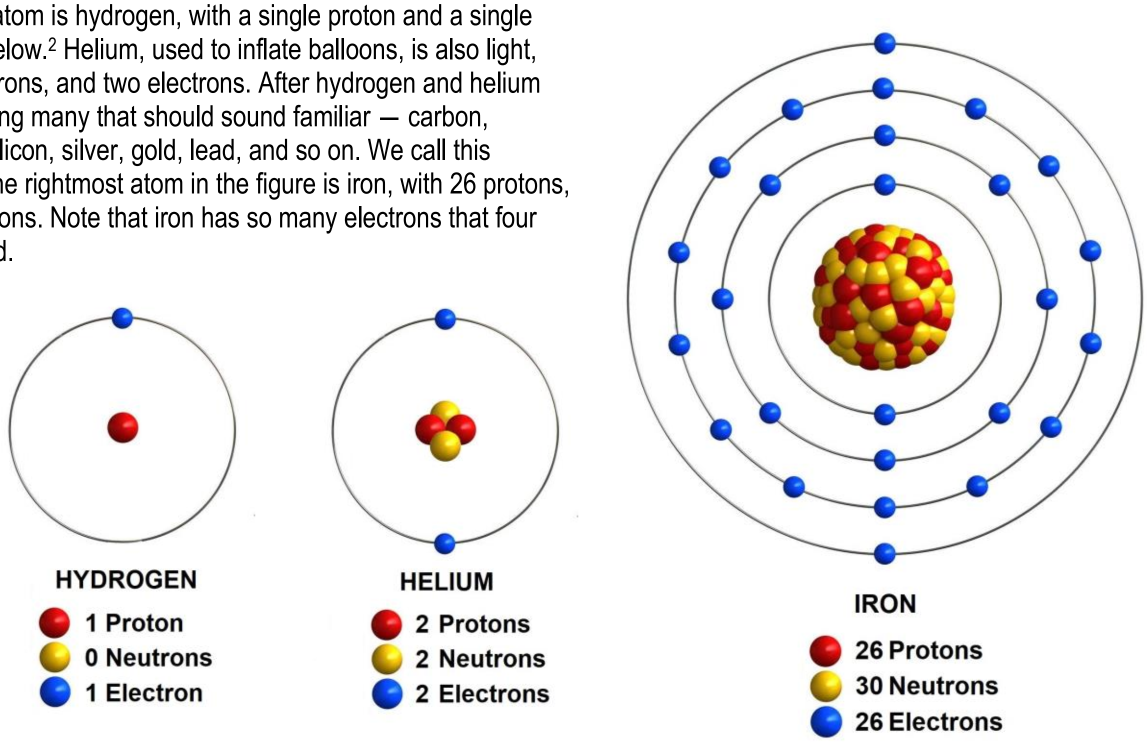
The idea that matter is composed of *atoms*, which cannot be broken down, has been around since the ancient Greeks. But it was not until the early 20th century that the structure of the atom was correctly described.

In 1913, physicists Niels Bohr and Ernest Rutherford proposed a model for the atom as a small, positively (+) charged *nucleus* orbited by negatively (-) charged *electrons*. The nucleus is composed of positively charged *protons*, and *neutrons*, which have no charge. The nucleus and electrons are bound together by electric forces, similar to the way in which planets are bound to the sun by gravity.

The simplest and lightest atom is hydrogen, with a single proton and a single electron. See the image below.[2] Helium, used to inflate balloons, is also light, with two protons, two neutrons, and two electrons. After hydrogen and helium come many others, including many that should sound familiar — carbon, nitrogen, oxygen, sulfur, silicon, silver, gold, lead, and so on. We call this collection the *elements*. The rightmost atom in the figure is iron, with 26 protons, 26 electrons, and 30 neutrons. Note that iron has so many electrons that four different *orbits* are required.

4. Why do you think the number of electrons in each atom equals the number of protons?

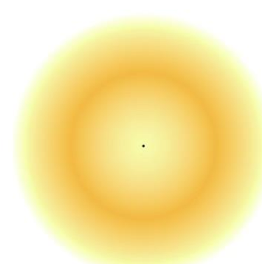
The number of protons in an atom's nucleus is called the *atomic number*. Hydrogen's atomic number is 1, helium's 2; iron's is 26.



Atom: An atom is the smallest particle of an element that retains the chemical characteristics of the element. Atoms consist of a nucleus of positively charged protons and neutrons, which have no charge, surrounded by negatively charged electrons. Protons, neutrons, and electrons are called *fundamental particles*.
Element: Elements are distinguished by how many protons are in the nucleus of an atom of the element, called the atomic number. Each element has a unique abbreviation: hydrogen = H, helium = He. Some are derived from Latin: iron = Fe (Latin: *ferrum*).

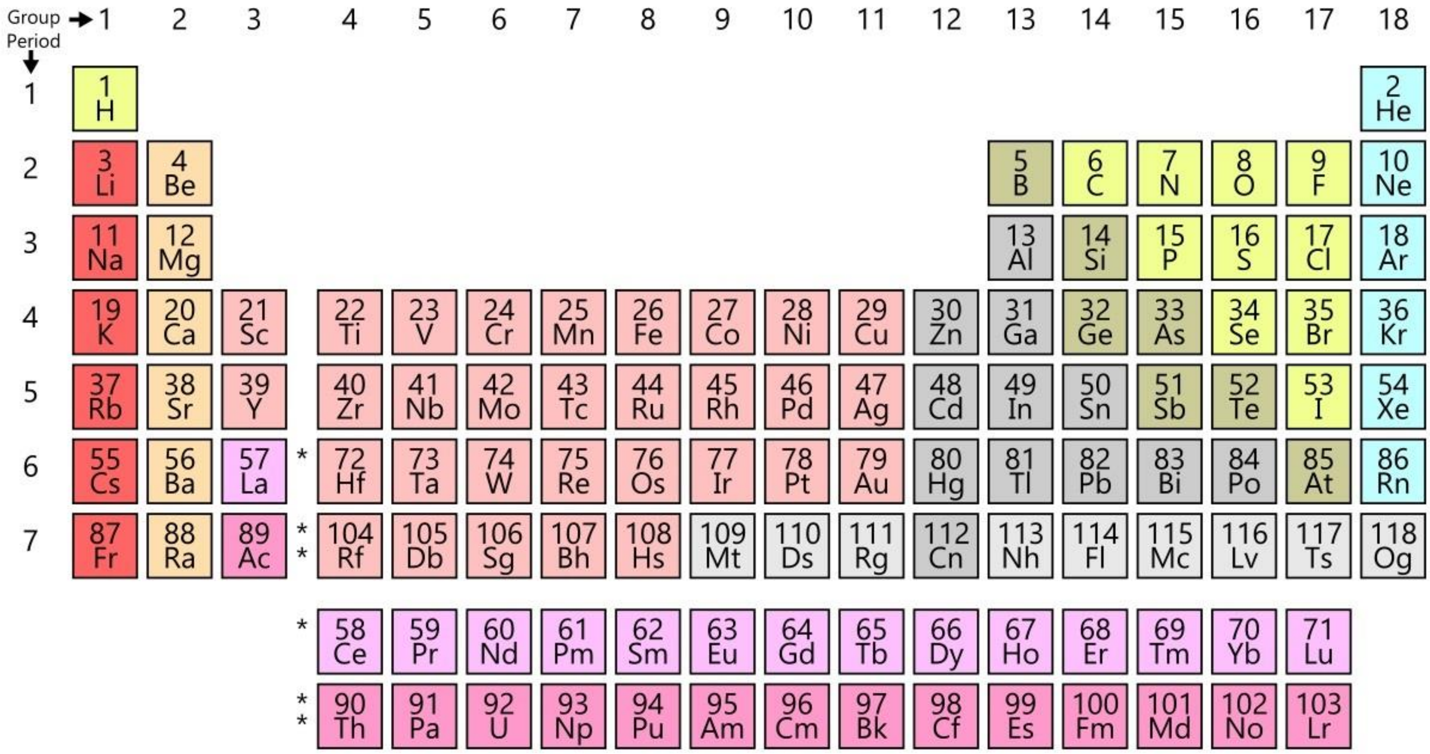
Iron has 30 neutrons to go with its 26 protons. This *isotope* of iron, ^{56}Fe, accounts for about 90% of the iron on Earth. The "56" is the sum of protons and neutrons, 26 + 30 = 56. Other isotopes, ^{54}Fe, ^{57}Fe, and ^{58}Fe, are also common in Earth's crust. Isotopes of an element have a fixed number of protons — 26 in the case of iron — but differ in their neutron count.

The figures above are not drawn to scale. A helium atom has a diameter of roughly 0.2 nanometers (about 100 times smaller than the smallest virus), and the nucleus of a helium atom is thousands of times smaller than the entire atom. Electrons are exceedingly tiny, each millions of times smaller than the nucleus. *Atoms are mostly empty space!* It is not possible to say exactly where an electron may be in an atom, except that it is somewhere in a spherical region around the nucleus. To the right is a more realistic picture of an atom, with an *electron cloud* surrounding a nucleus.[3] The electron cloud shows where the electron is most likely to be found.



Part 3. The Periodic Table

Chemists discovered elements gradually, and not in order. As they were discovered, chemists noticed similarities between the elements — their properties and the way they reacted, or what they did when put under a flame or stirred in water — and attempts were made to organize the elements accordingly. In 1869, Russian chemist Dmitri Mendeleev created the *periodic table of elements*. Shown below is the modernized version of Mendeleev's table that we continue to use today.[4]



Periodic Table of Elements

In the table above, each element is listed with its atomic number. The first element is hydrogen (H), in the upper left, followed by helium (He) in the upper right, then lithium (L), beryllium (Be), boron (B), carbon (C), and so on. The genius of Mendeleev's organization is that elements with similar characteristics are arranged together. For instance, the elements in the right-hand column — He, Ne, Ar, Kr, Xe, and Rn — are called the *noble gases*. All are odorless, colorless, and do not easily react to or bond with other elements (we'll discuss reaction and bonding on the next page).

5. Why is oxygen (O) not considered a noble gas?

6. Find copper (Cu), silver (Ag), gold (Au), and platinum (Pt). Are they grouped together? What properties do these elements share?

7. The elements in the row beginning with cerium (Ce) and praseodymium (Pr) form part of a set of elements called *rare earth* elements. Why do you think they are called that?

8. Elements with atomic numbers above 94 (plutonium: Pu) are not found in nature. How do you think we know about them?

Part 4. Molecules, Compounds, and Reactions

It was difficult work for chemists to isolate elements. One reason is that most elements have atoms that tend to join together with other atoms, either atoms of their own kind or with other elements. For example, water is made of two hydrogen atoms and one oxygen atom. The chemical notation for a water *molecule* is H_2O. The "H" stands for a hydrogen atom, the number 2 tells you how many hydrogen atoms there are, and the "O" stands for an oxygen atom.

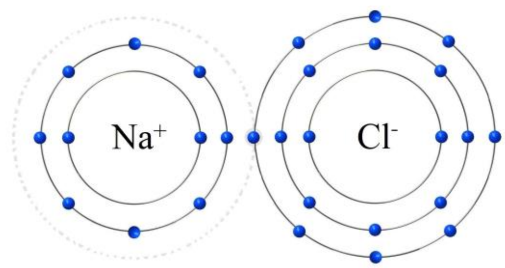
9. The "oxygen" in the air we breathe is composed of molecules, each containing two oxygen atoms grouped together. What is the chemical notation of this two-atom molecule?

- **Molecule:** A collection of atoms chemically *bonded* together in characteristic proportions. For example, two hydrogen atoms can bond together, forming H_2. Water (H_2O) is another molecule. Carbon dioxide (CO_2) is another.
- **Compound:** A molecule that consists of two or more elements that are chemically *bonded* to one another. For example, water (H_2O) is a compound, because it is a molecule that contains two different elements, but H_2 is not.
- **Reaction:** A chemical reaction occurs whenever a chemical bond is made or broken and involves the release or absorption of heat.

Both hydrogen and oxygen are highly *reactive*: they readily combine with other elements. For instance, most of the Earth's crust is *oxidized*. It is composed mostly of minerals in which oxygen has bonded with one or more other elements.

10. Silicon dioxide (quartz) is the second most abundant mineral on Earth. What is its chemical notation?

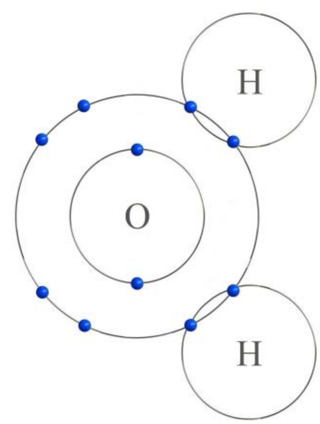
There are a few ways in which atoms can bond with each other. Sodium chloride (NaCl), which we know as salt, is formed when a sodium atom bonds with a chlorine atom. The sodium atom donates an electron to the chlorine atom, so that the pair become positively and negatively charged *ions*, Na^+ and Cl^-, and the NaCl bond is called an ***ionic bond***. In the figure to the right, notice that Na had just one electron in its outermost orbit shell (pale gray circle), which it donated to Cl, and Cl needed Na's electron to complete its outermost shell.[5]



NaCl ionic bond

11. Potassium chloride is similar to sodium chloride. It is also a salt. In fact, it tastes salty but is toxic in large quantities. What is its chemical notation?

Compounds form due to electrical forces between elements, and they do not necessarily share any of the properties of the elements that make them up. Sodium is a silvery metal, and chlorine is a poisonous yellow gas, but together they make table salt! Liquid water (H_2O) is made up of two elements, hydrogen and oxygen, which form diatomic (two atoms) molecules at room temperature. But when combined, two hydrogen atoms form a ***covalent bond*** with an oxygen atom. A covalent bond is electrical, like an ionic bond. But whereas an ionic bond has an electron donor and an electron recipient, a covalent bond has shared electron pairs. See the figure to the right.[5]



H_2O Covalent Bond

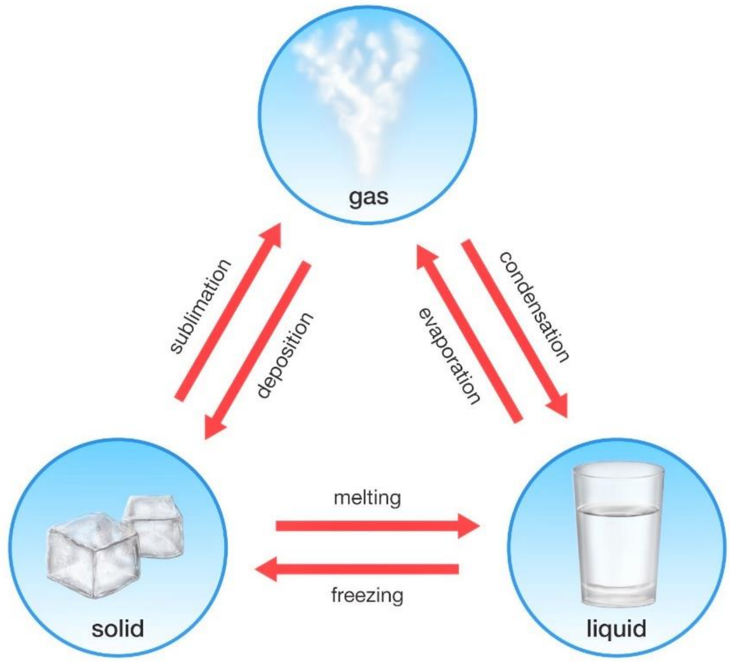
12. The atomic number of hydrogen (H) is 1, and the atomic number of oxygen (O) is 8. Is water (H_2O) electrically positive, negative, or neutral (neither positive nor negative)? Explain.

There is one more type of bond to mention. Water molecules are lopsided in shape. See the figure to the right. The lopsided look of the water molecule means it has a lopsided charge distribution and is attracted to other water molecules, though not enough to form a compound. This attraction is called a ***hydrogen bond***. This bond is responsible for making water stick to surfaces and for the ability of things like sugar and salt to easily dissolve in water.

Part 5. Phases of Matter

Many early thinkers believed there were four fundamental *elements*: earth, air, fire, and water. They believed that combinations of these four elements resulted in all the various substances.

We now know that the true elements are to be found in the periodic table. Earth, air, fire, and water are not elements; rather, they correspond to what we call *phases or matter*. Earth is *solid*, water *liquid*, and air is a *gas*. The figure to the right shows these phases and the names of their *phase transitions*.[6]



Phases of matter

13. Explain how water can be in any of the three phases.

14. Carbon dioxide is normally found as a gas in our atmosphere. When it is cooled to below -110 degrees F, it freezes and is called *dry ice.* Carbon dioxide is never a liquid, no matter what its temperature is. What are its phase transitions?

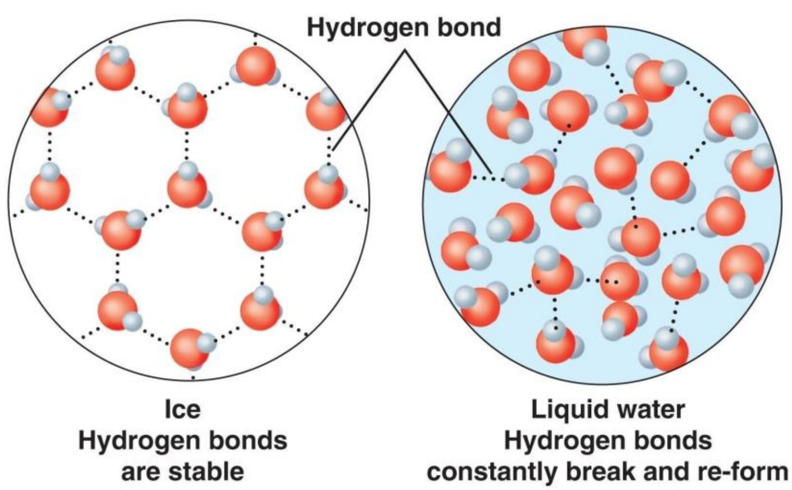
The first state of matter to be scientifically characterized was gas. In the middle of the 19th century, the work of several earlier chemists was combined to formulate the *ideal gas law*. The ideal gas law says that for a gas in a container, the product of the pressure and the volume of the gas (pressure × volume) is proportional to its temperature.

For instance, if the temperature of a gas in a container goes up, either the container must expand (the volume goes up) or the pressure of the gas on the container will go up.

15. What would happen to the pressure of a gas inside a rigid container if its temperature were lowered?

16. What do you think ultimately happens to a balloon filled with helium when it's let go? Consider that a balloon is flexible. It can expand or contract. As the balloon rises, the atmosphere gets colder and exerts less pressure on the balloon.

One form of solid matter is a crystal. It may happen that the shape molecules make on a microscopic scale when they form a crystal is reflected in the shape of the crystal we see. The hexagonal structure of frozen water (see the image to the right) is the reason snowflakes have six sides.[7]



Ice water and liquid water

17. From the image, explain why ice water floats on top of liquid water.

Part 6. Thermodynamics

The ideal gas law is connected to the study of *thermodynamics* (heat and motion), which sets out three laws.

1. The energy of an isolated system is constant. Energy is *conserved*. Energy cannot be created or destroyed. It *can* be converted from one form to another. We learned about some types of energy in unit 2: potential, kinetic, electrical, thermal (heat), nuclear, magnetic, and chemical.

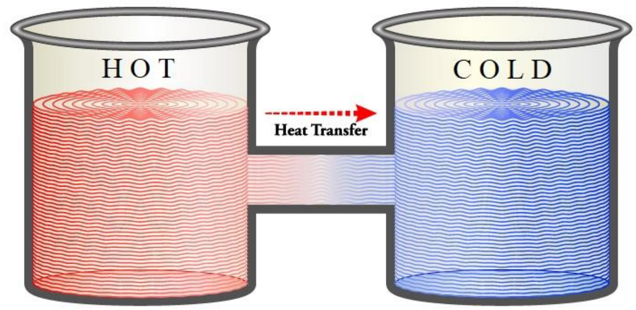
2. Heat cannot spontaneously flow from a colder location to a hotter location. Heat always flows from hot to cold.

3. As a system approaches absolute zero, all processes cease. Absolute zero is the lowest possible temperature: -459.67 degrees F.

See the figure to the right.[8] Two containers are filled with a liquid, one hot, one cold. They start out separated from each other.

18. If the two containers are connected, what ultimately happens?

19. Now, start with two connected containers, both filled with the same liquid, both at room temperature. Would you expect one container to spontaneously become hot and the other cold? Why or why not? Explain, using the second law.

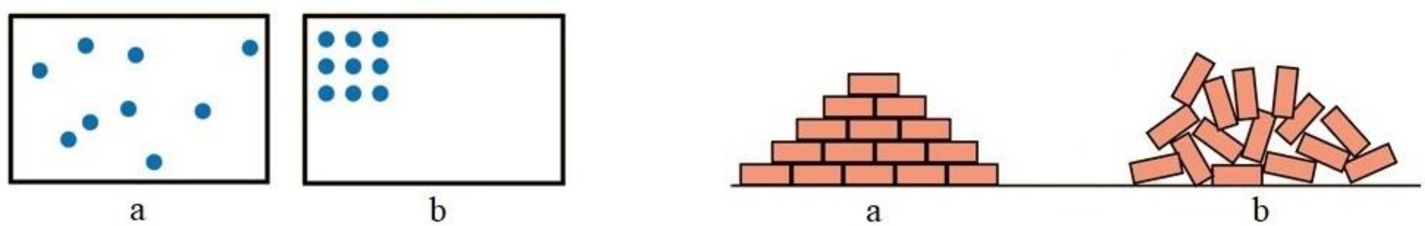


Second Law of Thermodynamics

One consequence of the second law of thermodynamics is that things tend to become more disordered over time. Order only happens when energy is added to a system. The measure of disorder in a system is called *entropy*. The idea of ever-increasing entropy is a powerful concept that applies to physical systems of all kinds, not just chemical.

20a. Give an example in which energy or work needs to be put into a system for order to be created.
20b. Give an example in which a system falls into disorder when energy or work is no longer put into it.

The figures below illustrate the basic ideas of entropy.[9]



Low and high entropy systems

21a. On the left, nine molecules of a gas are in a rectangular container. Which sort of configuration is more likely, a or b?
21b. On the right, bricks are dumped off the back of a truck. Which sort of arrangement is more likely to result, a or b?

Part 7. Radioactivity

In 1984, Stanley Watras, an employee at a U.S. nuclear plant, set off radiation monitors when he arrived at work. It would be natural to assume any contamination would be due to radiation exposure within the plant, except that Watras was sent home from work "clean" of radiation each evening. The source of contamination turned out to be radon levels in the basement of Watras' home. The radiation in Watras' basement was much worse than the radiation he was exposed to at work!

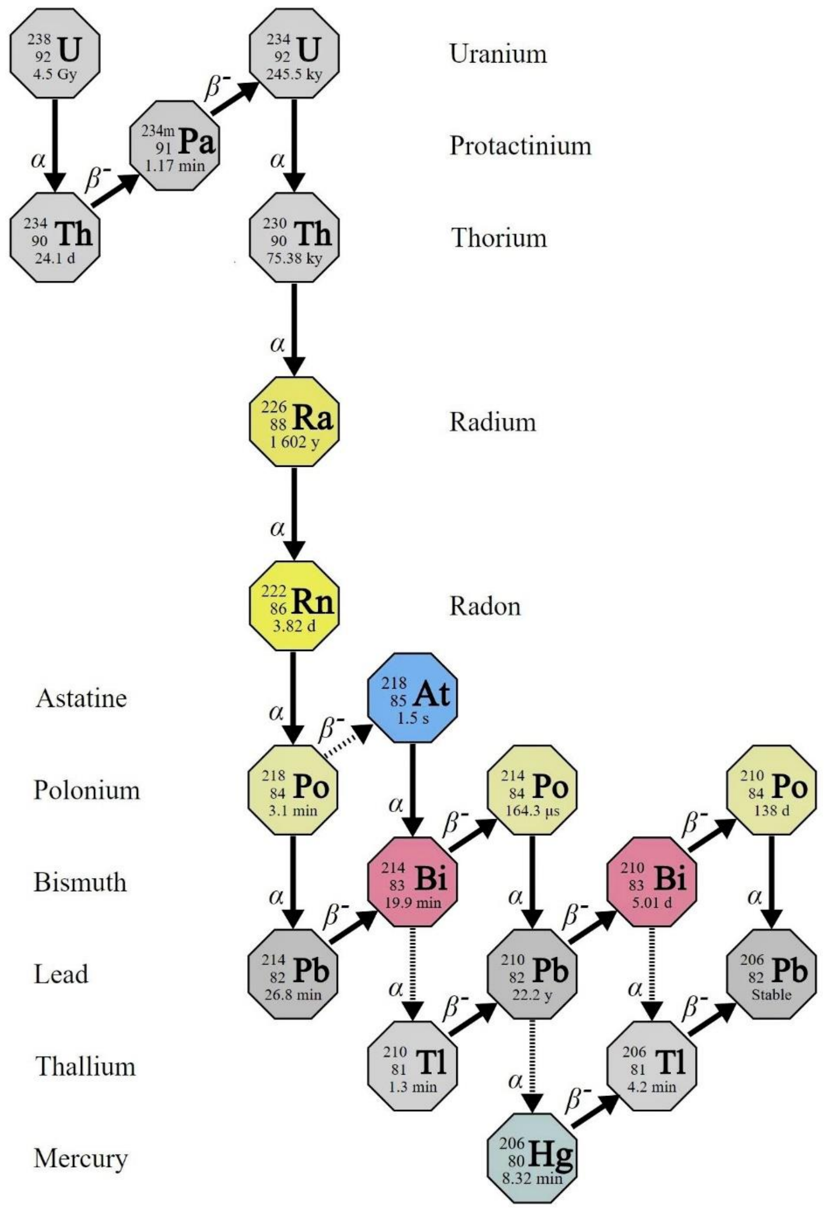
Radon is a byproduct of uranium decay. The element uranium is common in the Earth's crust — much more so than silver or gold. But unlike silver and gold, uranium slowly decays into other elements, releasing *radiation* as it does — in other words, it is *radioactive*.

In the figure to the right, uranium (^{238}**U**) is shown in the upper left.[10] Beneath the **U** it reads *4.5 Gy*, which means 4.5 billion years. This is uranium's *half-life*. If you have a hunk of uranium and wait 4 ½ billion years (roughly the age of Earth), about half of the uranium will have changed into lead. Following the arrows from upper left to lower right, you can trace uranium's *decay chain*. At each step in the chain, an element decays into a different element and radiation is released in the form of an *alpha particle* or a *beta particle*.
An **alpha particle** (α) is a raw helium nucleus: two protons and two neutrons. It has a +2 electrical charge.
A **beta particle** (β^-) is an electron. It has a -1 electrical charge.

22. Why do you think charged α and β^- particles might pose a health hazard for humans?

23. Notice that radon (Rn) has a very short half-life of 3.82 days. Why doesn't it just dwindle down to nothing?

Several elements in the figure were discovered only because they are formed when uranium decays. Radium (**Ra**) was discovered by Marie and Pierre Curie in 1898. Astatine (**At**) is so rare less than one gram exists in the Earth's crust at any given time. The Curies also discovered polonium (**Po**), which Marie Curie named after her homeland, Poland. Exposure or ingestion of even tiny amounts of polonium can cause severe illness or death. Marie Curie died in 1934 as a result of her research into radioactive materials.



Uranium-238 decay chain

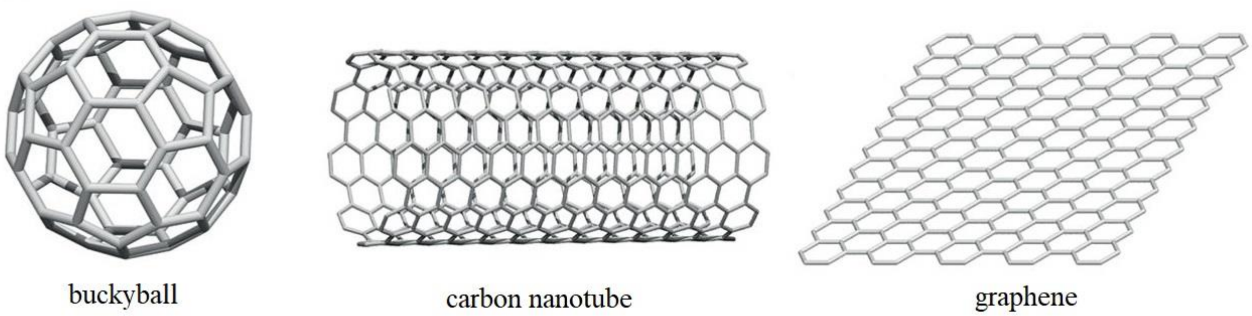
Notice that lead (^{206}**Pb**, in the lower right of the figure) is marked *stable*. It is the only product of uranium decay that doesn't decay further. All uranium eventually turns into lead.

Part 8. The Origin of Elements

Stars are huge manufacturing centers of elements. Only hydrogen, helium, and perhaps some lithium and beryllium (the first four elements) were produced during the Big Bang (discussed in unit 1). Dying stars are responsible for producing all the remaining elements up to iron, by a process called *nuclear fusion*. The extreme heat and gravitational forces inside the core of a star cause the nuclei of atoms to fuse together. This is the opposite of the uranium decay process described on the previous page. Scientists believe that elements heavier than iron (e.g., gold, lead, uranium) are created when a pair of neutron stars collides. In unit 1 we learned that neutron stars are bizarre objects — very small, but so dense a teaspoon of neutron star material would weigh over ten million tons. It is amazing to think that the elements produced by events like these helped form our young Earth! As astronomer Carl Sagan said, "we are star stuff." We are made from atoms that came from the Big Bang, dying stars, and the collisions of neutron stars.

Part 9. Chemistry in Everyday Life

Today, we use chemistry to create new things. Most fuels we use are chemically engineered. Cars have alternators and batteries and they burn fuel, so driving a car is like a chemistry experiment. Plastics — bags, containers, appliances, paints, dyes, building materials, fabrics and paper — are all chemically engineered materials. Humans are made up of about 25 elements, but a smartphone contains about 75! The figure below shows several molecular high-strength structures engineered out of carbon.[11]



Carbon Nanostructures

24. What are some products of chemistry, or chemically engineered materials, you know about or use?

"Satisfaction of one's curiosity is one of the greatest sources of happiness in life." —American chemist Linus Pauling

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Remember: First names only & please let us know if your address changes

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Answers and hints to selected questions

4. To balance out the charge so that the atom is electrically neutral
5. Oxygen reacts easily with other elements. Consider H_2O, CO_2.
9. O_2; 10. SiO_2; 11. KCl
12. Each hydrogen atom has one proton and the oxygen atom has eight protons. There are ten electrons, so H_2O is electrically neutral.
13. Ice, liquid water, and water vapor (for instance, steam)
14. CO_2 undergoes phase changes sublimation and deposition only.
17. Ice is less dense than liquid water.
22. They can react with molecules in human cells.
23. More radon is continually being produced by the decay of uranium.