Chemistry

for Utah SEEd Standards

2020-2021

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Utah State Board of Education OER
2020-2021

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We especially wish to thank the amazing Utah science teachers whose collaborative efforts made the book possible. Thank you for your commitment to science education and Utah students!

Students as Scientists

What does science look and feel like?

If you're reading this book, either as a student or a teacher, you're going to be digging into the "practice" of science. Probably, someone, somewhere, has made you think about this before, and so you've probably already had a chance to imagine the possibilities. Who do you picture doing science? What do they look like? What are they doing?

Often when we ask people to imagine this, they draw or describe people with lab coats, people with crazy hair, beakers and flasks of weird looking liquids that are bubbling and frothing. Maybe there's even an explosion. Let's be honest: Some scientists do look like this, or they look like other stereotypes: people readied with their pocket protectors and calculators, figuring out how to launch a rocket into orbit. Or maybe what comes to mind is a list of steps that you might have to check off for your science fair project to be judged; or, maybe a graph or data table with lots of numbers comes to mind.

So let's start over. When you imagine graphs and tables, lab coats and calculators, is that what you love? If this describes you, that's great. But if it doesn't, and that's probably true for many of us, then go ahead and dump that image of science. It's useless because it isn't you. Instead, picture yourself as a maker and doer of science. The fact is, we need scientists and citizens like you, whoever you are, because we need all of the ideas, perspectives, and creative thinkers. This includes you.

Scientists wander in the woods. They dig in the dirt and chip at rocks. They peer through microscopes. They read. They play with tubes and pipes in the aisles of a hardware store to see what kinds of sounds they can make with them. They daydream and imagine. They count and measure and predict. They stare at the rock faces in the mountains and imagine how those came to be. They dance. They draw and write and write and write some more.

Scientists — and this includes all of us who do, use, apply, or think about science — don't fit a certain stereotype. What really sets us apart as humans is not just that we know and do things, but that we wonder and make sense of our world. We do this in many ways, through painting, religion, music, culture, poetry, and, most especially, science. Science isn't just a method or a collection of things we know. It's a uniquely human practice of wondering about and creating explanations for the natural world around us. This ranges from the most fundamental building blocks of all matter to the widest expanse of space that contains it all. If you've ever wondered "When did time start?", or "What is the smallest thing?", or even just "What is color?", or so many other endless questions then you're already thinking with a scientific mind. Of course you are; you're human, after all.

But here is where we really have to be clear. Science isn't just questions and explanations. Science is about a sense of wondering and the sense-making itself. We have to wonder and then really dig into the details of our surroundings. We have to get our hands dirty. Here's a good example: two young scientists under the presence of the Courthouse Towers in Arches National Park. We can be sure that they spent some amount of time in awe of the giant sandstone walls, but here in this photo they're enthralled with the sand that's just been re-washed by recent rain. There's this giant formation of sandstone looming above these kids in the desert, and they're happily playing in the sand. This is ridiculous. Or is it?

How did that sand get there? Where did it come from? Did the sand come from the rock or does the rock come from sand? And how would you know? How do you tell this story?

Look. There's a puddle. How often is there a puddle in the desert? The sand is wet and fine; and it makes swirling, layered patterns on the solid stone. There are pits and pockets in the rock, like the one that these two scientists are sitting in, and the gritty sand and the cold water accumulate there. And then you might start to wonder: Does the sand fill in the hole to form more rock, or is the hole worn away because it became sand? And then you might wonder more about the giant formation in the background: It has the same colors as the sand, so has this been built up or is it being worn down? And if it's being built up by sand, how does it all get put together; and if it's being worn away then why does it make the patterns that we see in the rock? Why? How long? What next?

Just as there is science to be found in a puddle or a pit or a simple rock formation, there's science in a soap bubble, in a worm, in the spin of a dancer and in the structure of a bridge. But this thing we call "science" is only there if you're paying attention, asking questions, and imagining possibilities. You have to make the science by being the person who gathers information and evidence, who organizes and reasons with this, and who communicates it to others. Most of all, you get to wonder. Throughout all of the rest of this book and all of the rest of the science that you will ever do, wonder should be at the heart of it all. Whether you're a student or a teacher, this wonder is what will bring the sense-making of science to life and make it your own.

Adam Johnston
Weber State University

Science and Engineering Practices

Science and Engineering Practices are what scientists do to investigate and explore natural phenomena

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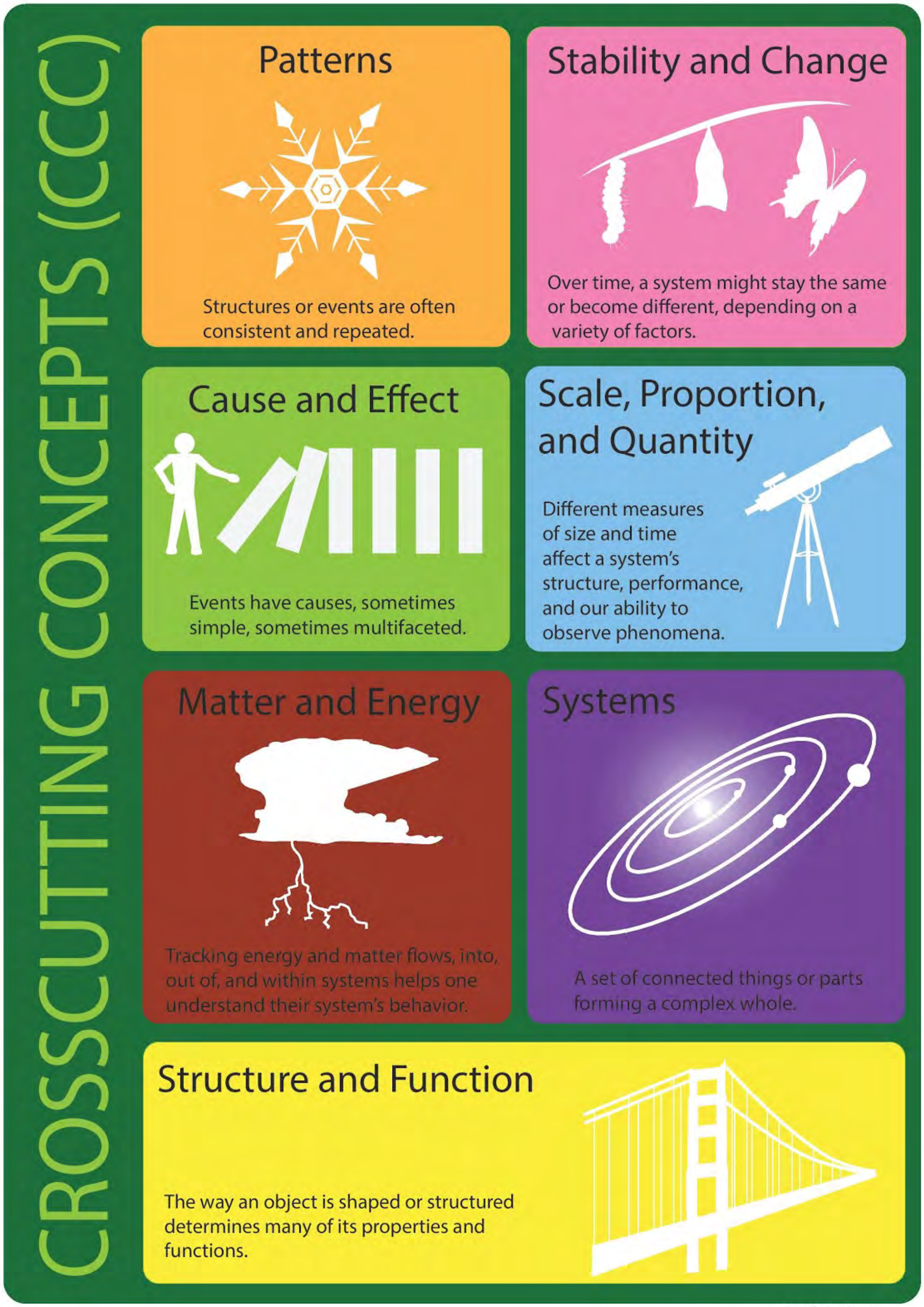
Created by Susan Larson

Cross Cutting Concepts

Crosscutting Concepts are the tools that scientists use to make sense of natural phenomena.



CROSSCUTTING CONCEPTS (CCC)

Patterns

Structures or events are often consistent and repeated.

Stability and Change

Over time, a system might stay the same or become different, depending on a variety of factors.

Cause and Effect

Events have causes, sometimes simple, sometimes multifaceted.

Scale, Proportion, and Quantity

Different measures of size and time affect a system's structure, performance, and our ability to observe phenomena.

Matter and Energy

Tracking energy and matter flows, into, out of, and within systems helps one understand their system's behavior.

Systems

A set of connected things or parts forming a complex whole.

Structure and Function

The way an object is shaped or structured determines many of its properties and functions.

Created by Susan Larson

A Note to Teachers

This Open Educational Resource (OER) textbook has been written specifically for students as a reputable source for them to obtain information aligned to the Chemistry Standards. The hope is that as teachers use this resource with their students, they keep a record of their suggestions on how to improve the book. Every year, the book will be revised using teacher feedback and with new objectives to improve the book.

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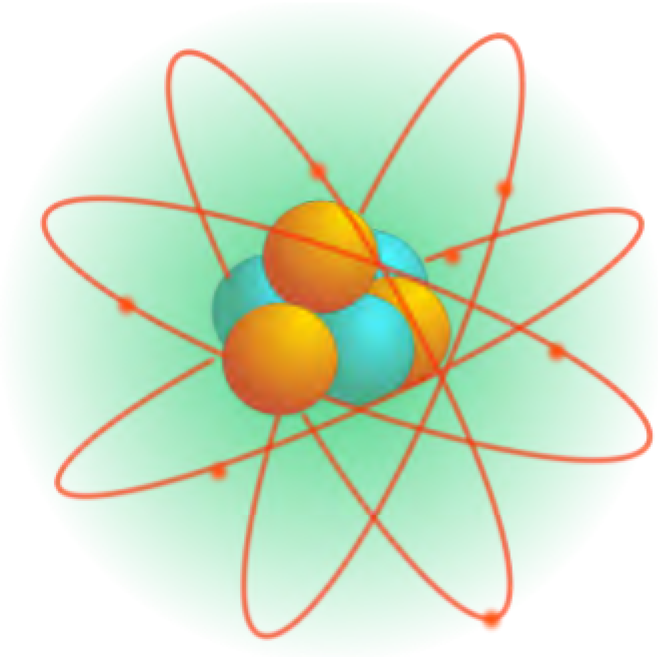
CHAPTER 1

Strand 1: The Structure and Properties of Atoms

Chapter Outline



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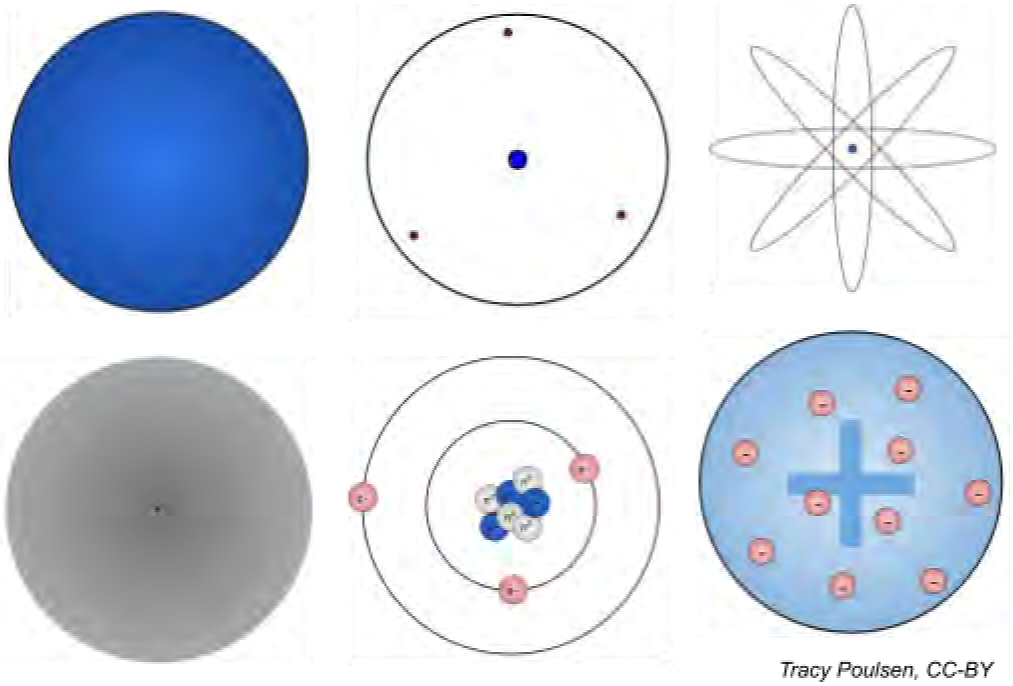
Atoms have substructures of their own including a small central nucleus containing protons and neutrons surrounded by a larger region containing electrons. The strong nuclear interaction provides the primary force that holds nuclei together. Without it, the electromagnetic forces between protons would make all nuclei other than hydrogen unstable.

Processes of fusion, fission, and radioactive decay of unstable nuclei involve changes in nuclear binding energies. Elements are placed in columns and rows on the periodic table to reflect their common and repeating properties.

1.1 Atomic Structure (Chem.1.1)

Explore this Phenomenon



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The images are different models of the atom throughout history.

Look for patterns in the structure and function of these models of atoms. Then answer the following questions:

1. Why are there differences between the models?
2. How are the models similar?
3. Can you predict the order these models were created?

Standard Chem.1.1

Obtain, evaluate, and communicate information regarding the structure of the atom on the basis of experimental evidence. Emphasize the relationship between proton number and element identity, isotopes, and electrons in atoms. Examples of experimental evidence could include the gold foil experiment, cathode ray tube, or atomic spectrum data. (PS1.A)

Throughout history the model of the atom has changed. As you read this section, look for how different evidence is used to draw conclusions about the structure of atoms.

What Are Atoms?

Atoms are the building blocks of matter. They are the smallest particles of an element that still have the element's properties. Elements, in turn, are pure substances—such as nickel, hydrogen, and helium—that make up all kinds of matter. All the atoms of a given element are identical in that they have the same number of protons, one of the building blocks of atoms. They are also different from the atoms of all other elements, as atoms of different elements have a different number of protons.

Size of Atoms

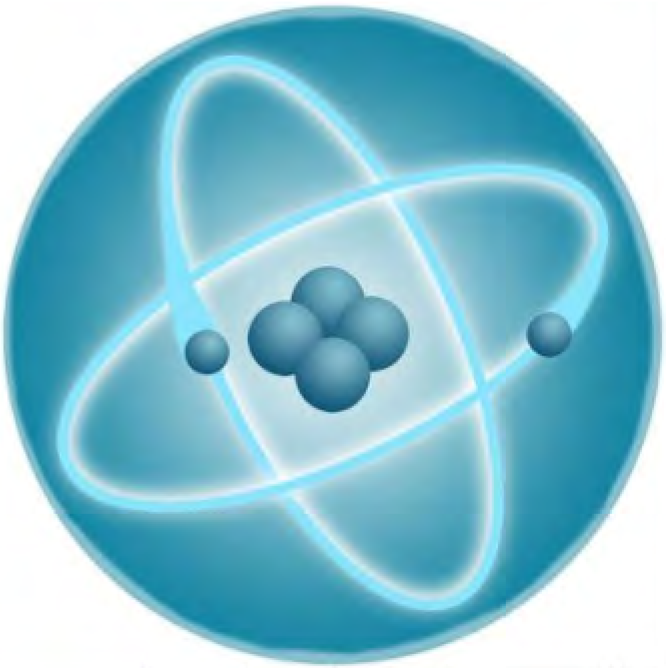
Unlike bricks, atoms are extremely small. The radius of an atom is well under 1 nanometer, which is one-billionth of a meter. If a size that small is hard to imagine, consider this: trillions of atoms would fit inside the period at the end of this sentence.

Subatomic Particles

Although atoms are very tiny, they consist of even smaller particles. Three main types of particles that make up all atoms are:

- protons, which have a positive electric charge.
- electrons, which have a negative electric charge.
- neutrons, which are neutral in electric charge.

The model below shows how these particles are arranged in an atom. The particular atom represented by the model is helium, but the particles of all atoms are arranged in the same way. At the center of the atom is a dense area called the nucleus, where all the protons and neutrons are clustered closely together. The electrons constantly move around the nucleus. Helium has two protons and two neutrons in its nucleus and two electrons moving around the nucleus. Atoms of other elements have different numbers of subatomic particles, but the number of protons always equals the number of electrons. This makes atoms neutral in charge because the positive and negative charges "cancel out."



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Model of a helium atom.

Early Ideas of Atoms

All matter in the universe is made of atoms (basic unit of matter). All modern scientists accept the concept of the atom, but when the concept of the atom was first proposed about 2,500 years ago, ancient philosophers laughed at the idea. It has always been difficult to convince people of the existence of things that are too small to see. We will spend some time considering the evidence (observations) that convince scientists of the existence of atoms.

Democritus and the Greek Philosophers

One of the first people to propose “atoms” was a man known as Democritus. As an alternative to the beliefs of many Greek philosophers, he suggested that atomos, or atomon—tiny, indivisible, solid objects - make up all matter in the universe.

Sadly, it took over two millennia before the theory of atomos (or “atoms”, as they’re known today) was fully appreciated.

While it must be assumed that many more scientists, philosophers, and others studied the composition of matter after Democritus, a major leap forward in our understanding of the composition of matter took place in the 1800s with the work of the British scientist John Dalton.

Dalton studied the weights of various elements and compounds. He noticed that matter always combined in fixed mathematical ratios based on weight, or volume in the case of gases. Chemical compounds always contain the same proportion of elements by mass, regardless of amount. Dalton also observed that there could be more than one combination of two elements.

Dalton's Atomic Theory (1804)

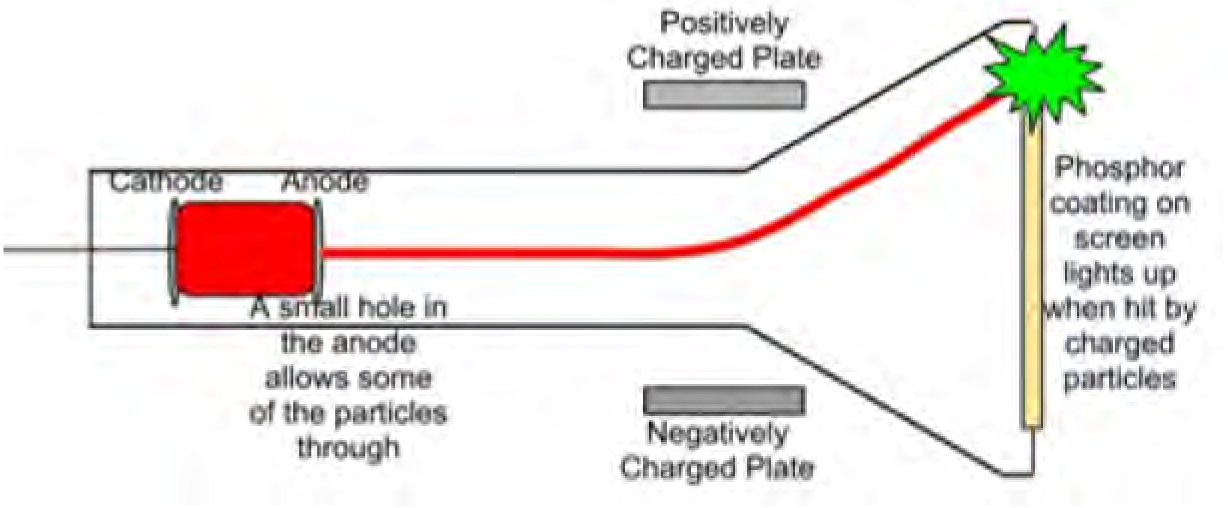
John Dalton, public domain

From his experiments and observations, as well as the work from peers of his time, Dalton proposed a new theory of the atom known as Dalton's atomic theory. The general tenets of this theory were as follows:

- All matter is composed of extremely small particles called atoms.
- Atoms of a given element are identical in size, mass, and other properties. Atoms of different elements differ in size, mass, and other properties.
- Atoms cannot be subdivided, created, or destroyed.
- Atoms of different elements can combine in simple whole number ratios to form chemical compounds.
- In chemical reactions, atoms are combined, separated, or rearranged.

Thomson’s Plum Pudding Model

In the mid-1800s, scientists were beginning to realize that the study of chemistry and the study of electricity were actually related. First, a man named Michael Faraday showed how passing electricity through mixtures of different chemicals could cause chemical reactions. Shortly after that, the scientists found that by forcing electricity through a tube filled with gas, the electricity made the gas glow! Scientists didn't understand the relationship between chemicals and electricity until a British physicist named J. J. Thomson began experimenting with what is known as a cathode ray tube.



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Thomson's experiment with cathode rays found that the ray moved away from negatively charged plates and toward positively charged plates. What does this say about the charge of the ray?

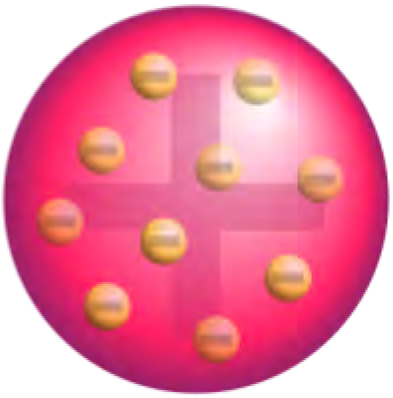
J. J. Thomson did some rather complex experiments with magnets, and used his results to prove that cathode rays were not only negatively charged, but also had mass. Remember that anything with mass is part of what we call matter. In other words, these cathode rays must be the result of negatively charged "matter" flowing from the cathode to the anode. But there was a problem. According to J. J. Thomson's measurements, either these cathode rays had a ridiculously high charge, or else had very, very little mass – much less mass than the smallest known atom.

How was this possible? How could the matter making up cathode rays be smaller than an atom if atoms were indivisible? J. J. Thomson made a radical proposal: maybe atoms are divisible. J. J. Thomson suggested that the small, negatively charged particles making up the cathode ray were actually pieces of atoms. He called these pieces "corpuscles", although today we know them as electrons. Thanks to his clever experiments and careful reasoning, J. J. Thomson is credited with the discovery of the electron.

Now imagine what would happen if atoms were made entirely of electrons. First of all, electrons are very, very small; in fact, electrons are about 2,000 times smaller than the smallest known atom, so every atom would have to contain a whole lot of electrons. But there's another, even bigger problem: electrons are negatively charged. Therefore, if atoms were made entirely out of electrons, atoms would be negatively charged themselves and that would mean all matter was negatively charged as well. Of course, matter isn't negatively charged. In fact, most matter is what we call neutral – it has no charge at all. If matter is composed of atoms, and atoms are composed of negative electrons, how can matter be neutral?

The only possible explanation is that atoms consist of more than just electrons. Atoms must also contain some type of positively charged material that balances the negative charge on the electrons. Negative and positive charges of equal size cancel each other out, just like negative and positive numbers of equal size. What do you get if you add +1 and -1? You get 0, or nothing. That's true of numbers, and that's also true of charges. If an atom contains an electron with a -1 charge, but also some form of material with a +1 charge, overall the atom must have a$(+1)+(-1)=0$ charge – in other words, the atom must be neutral, or have no charge at all.

Plum pud by Lachlan Hardy, https://flic.kr/p/7rVZbR, CC-BY



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Thomson's plum pudding model was much like a chocolate chip cookie. Notice how the chocolate chips represent the negatively charged electrons, while the positive charge is spread throughout the entire "batter".

When Thomson discovered the negative electron, he realized that atoms had to contain positive material as well – otherwise they wouldn't be neutral overall. As a result, Thomson formulated what's known as the "plum pudding" model for the atom. According to the "plum pudding" model, the negative electrons were like pieces of fruit and the positive material was like the batter or pudding. This made a lot of sense given Thomson's experiments and observations. Thomson had been able to isolate electrons using a cathode ray tube; however, he had never managed to isolate positive particles.

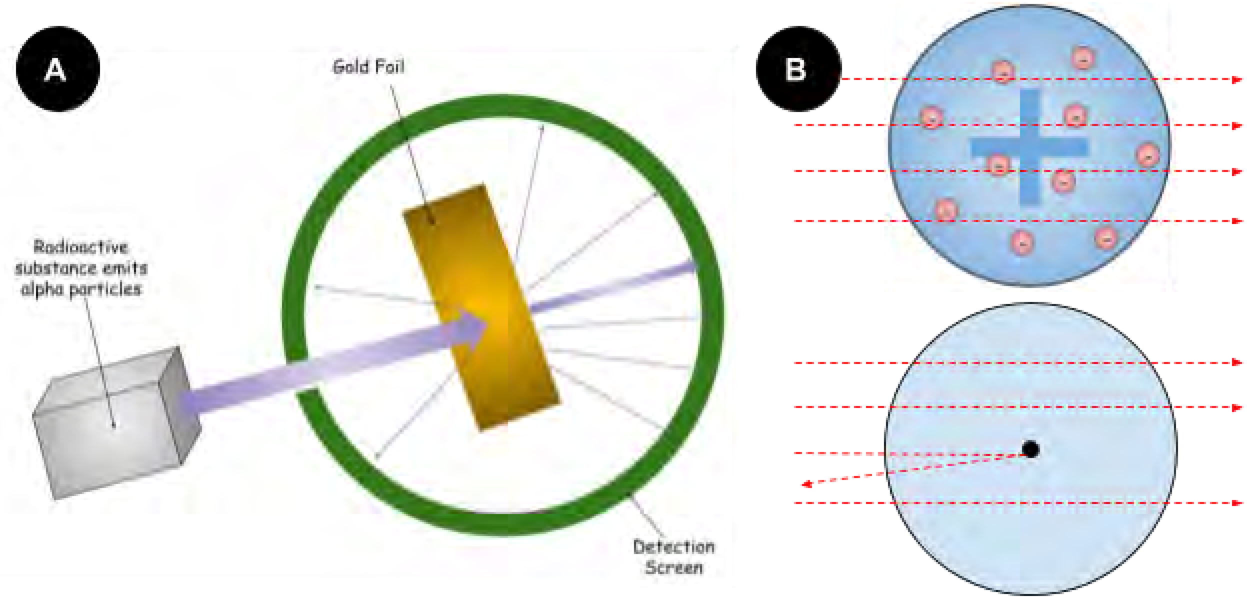
Rutherford's Nuclear Model

Everything about Thomson's experiments suggested the "plum pudding" model was correct – but according to the scientific method, any new theory or model should be tested by further experimentation and observation. In the case of the "plum pudding" model, it would take a man named Ernest Rutherford to prove it inaccurate.

Disproving Thomson's "plum pudding" model began with the discovery that an element known as uranium emits positively charged particles called alpha particles as it undergoes radioactive decay. Radioactive decay occurs when one element decomposes into another element. It only happens with a few very unstable elements.

Ernest Rutherford was fascinated by all aspects of alpha particles. For the most part, though, he seemed to view alpha particles as tiny bullets that he could use to fire at all kinds of different materials. One experiment in particular, however, surprised Rutherford and everyone else.

Rutherford found that when he fired alpha particles at a very thin piece of gold foil, an interesting thing happened (A). Almost all of the alpha particles went straight through the foil as if they'd hit nothing at all. This was what he expected to happen. If Thomson's model was accurate, there was nothing hard enough for these small particles to hit that would cause any change in their motion.



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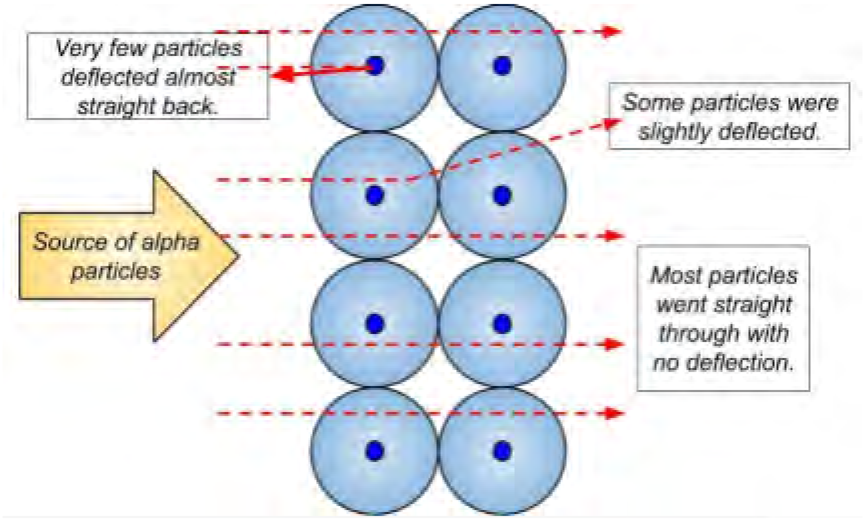
Every so often, though, one of the alpha particles would be deflected slightly as if it had bounced off of something hard. Even less often, Rutherford observed alpha particles bouncing straight back at the “gun” from which they had been fired! (B) It was as if these alpha particles had hit a wall “head-on” and had ricocheted right back in the direction that they had come from, indicating they were hitting a very small, very dense particle in the atom.



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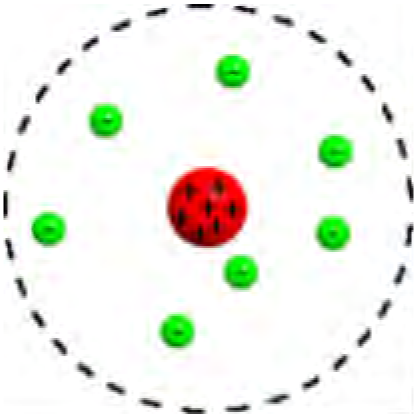
Rutherford thought that these experimental results were rather odd. Rutherford described firing alpha particles at gold foil like shooting a high-powered rifle at tissue paper. Would you ever expect the bullets to hit the tissue paper and bounce back at you? Of course not! The bullets would break through the tissue paper and keep on going, almost as if they’d hit nothing at all. Therefore, the fact that most alpha particles passed through didn’t shock him. On the other hand, how could he explain the alpha particles that got deflected? Furthermore, how could he explain the alpha particles that bounced right back as if they’d hit a wall?

Rutherford concluded that the only way to explain his results was to assume that the positive matter forming the gold atoms was not, in fact, distributed like the batter in plum pudding, but rather, was concentrated in one spot, forming a small positively charged particle somewhere in the center of the gold atom. We now call this clump of positively charged mass the nucleus - (the small, dense, positively charged center of the atoms). According to Rutherford, the presence of a nucleus explained his experiments, because it implied that most alpha particles passed through the gold foil without hitting anything at all. Once in a while, though, the alpha particles would actually collide with a gold nucleus, causing the alpha particles to be deflected, or even to bounce right back in the direction they came from.

While Rutherford’s discovery of the positively charged atomic nucleus offered insight into the structure of the atom, it also led to some questions. According to the “plum pudding” model, electrons were like plums embedded in the positive “batter” of the atom. Rutherford’s model, though, suggested that the positive charge wasn’t distributed like batter, but rather, was concentrated into a tiny particle at the center of the atom, while most of the rest of the atom was empty space. What did that mean for the electrons? If they weren’t embedded in the positive material, exactly what were they doing? And how were they held in the atom? Rutherford suggested that the electrons might be circling or “orbiting” the positively charged nucleus as some type of negatively charged cloud, but at the time, there wasn’t much evidence to suggest exactly how the electrons were held in the atom.



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Rutherford suggested that electrons surround a central nucleus.

Despite the problems and questions associated with Rutherford’s experiments, his work with alpha particles definitely seemed to point to the existence of an atomic “nucleus.” Between J. J. Thomson, who discovered the electron, and Rutherford, who suggested that the positive charges in an atom were concentrated at the atom’s center, the 1890s and early 1900s saw huge steps in understanding the atom at the subatomic level. It was clear that an atom contains negatively charged electrons and a nucleus containing positive charges. In the next section, we’ll look more carefully at the structure of the nucleus, and we’ll learn that while the atom is made up of positive and negative particles, it also contains neutral particles that neither Thomson, nor Rutherford, were able to detect with their experiments.

The Quest for the Neutron

Clues are generally considered to involve the presence of something – a footprint, a piece of fabric, a bloodstain, something tangible that we can measure directly. The discoveries of the electron and the proton were accomplished with the help of those kinds of clues. Cathode ray tube experiments showed both the negatively charged electrons emitted by the cathode and a positively charged proton (also emitted by the cathode). The neutron was initially found not by a direct observation, but by noting what was not found.

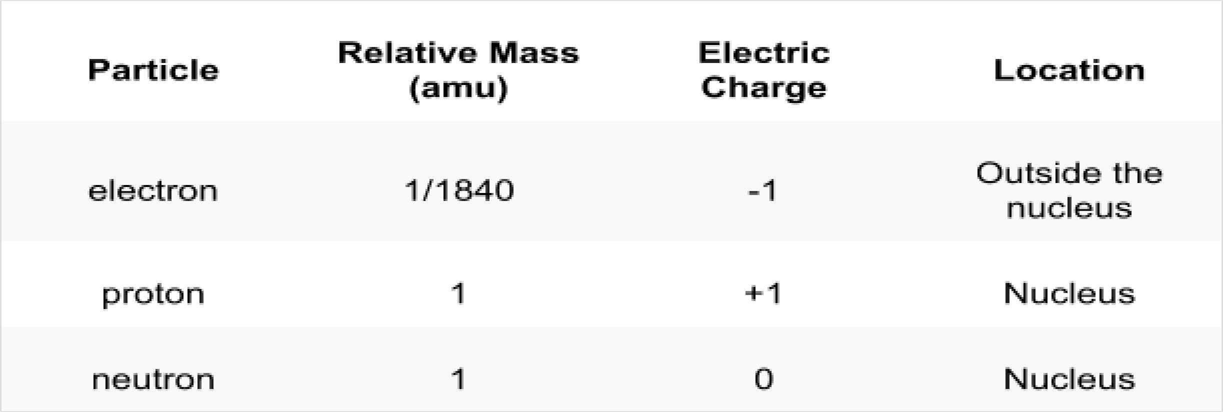
Research has shown the properties of the electron and the proton. Scientists learned that approximately 1837 electrons weighed the same as one proton. There was evidence to suggest that electrons went around the heavy nucleus composed of protons. Charge was balanced with equal numbers of electrons and protons which make up an electrically neutral atom. But there was a problem with this model – the atomic number (number of protons) did not match the atomic weight. In fact, the atomic number was usually about half the atomic weight. This indicated that something else must be present. That something must weigh about the same as a proton, but could not have a charge – this new particle had to be electrically neutral.

In 1920, Ernest Rutherford tried to explain this phenomenon. He proposed that the "extra" particles were combinations of protons and electrons in the nucleus. These new particles would have a mass very similar to a proton, but would be electrically neutral since the positive charge of the proton and the negative charge of the electron would cancel each other out.

In 1930, German researchers bombarded the element beryllium with alpha particles (helium nuclei containing two protons and two neutrons with a charge of +2). The particles produced in this process had strong penetrating power, which suggested they were fairly large. In addition, they were not affected by a magnetic field, so they were electrically neutral. The French husband-wife research team of Frederic and Irene Joliot-Curie used these new "rays" to bombard paraffin, which was rich in protons. The unknown particles produced a large emission of protons from the paraffin.

The English physicist James Chadwick (1891-1974) repeated these experiments and studied the energy of these particles. By measuring velocities, he was able to show that the new particle has essentially the same mass as a proton. So we now have a third subatomic particle with a mass equal to that of a proton, but with no charge. This particle is called the neutron. Chadwick won the Nobel Prize in Physics in 1935 for his research.

Even though electrons, protons, and neutrons are all types of subatomic particles, they are not all the same mass. When you compare the masses of electrons, protons and neutrons, what you find is that electrons have an extremely small mass, compared to either protons or neutrons. On the other hand, the masses of protons and neutrons are fairly similar, although technically, the mass of a neutron is slightly larger than the mass of a proton. Because protons and neutrons are so much more massive than electrons, almost all of the mass of any atom comes from the nucleus, which contains all of the neutrons and protons.



Particle	Relative Mass (amu)	Electric Charge	Location
electron	1/1840	-1	Outside the nucleus
proton	1	+1	Nucleus
neutron	1	0	Nucleus

The previous table shown gives the properties and locations of electrons, protons, and neutrons. The third column shows the masses of the three subatomic particles in grams. The second column shows the masses of the three subatomic particles in “atomic mass units”. Atomic mass units (amu) - (one-twelfth the mass of a carbon-12 atom) are useful because the mass of a proton and the mass of a neutron are almost exactly 1.0 in this unit system.

In addition to mass, another important property of subatomic particles is their charge. You already know that neutrons are neutral, and thus have no charge at all. Therefore, we say that neutrons have a charge of zero. What about electrons and protons? You know that electrons are negatively charged and protons are positively charged, but what’s amazing is that the positive charge on a proton is exactly equal in magnitude (magnitude means “absolute value” or “size when you ignore positive and negative signs”) to the negative charge on an electron. The third column in the table shows the charges of the three subatomic particles. Notice that the charge on the proton and the charge on the electron have the same magnitude.

Negative and positive charges of equal magnitude cancel each other out. This means that the negative charge on an electron perfectly balances the positive charge on the proton. In other words, a neutral atom must have exactly one electron for every proton. If a neutral atom has 1 proton, it must have 1 electron. If a neutral atom has 2 protons, it must have 2 electrons. If a neutral atom has 10 protons, it must have 10 electrons.

Atomic Number and Mass Number

If all atoms contain protons, neutrons, and electrons what makes each one unique? Scientists can distinguish between different elements by counting the number of protons. If an atom has only one proton, we know it’s a hydrogen atom. An atom with two protons is always a helium atom. If scientists count four protons in an atom, they know it’s a beryllium atom. An atom with three protons is a lithium atom, an atom with five protons is a boron atom, an atom with six protons is a carbon atom... the list goes on.

It is sometimes difficult to distinguish one element from another. Each element however, does have a unique number of protons. Sulfur has 16 protons. Silicon has 14 protons, and gold has 79 protons.

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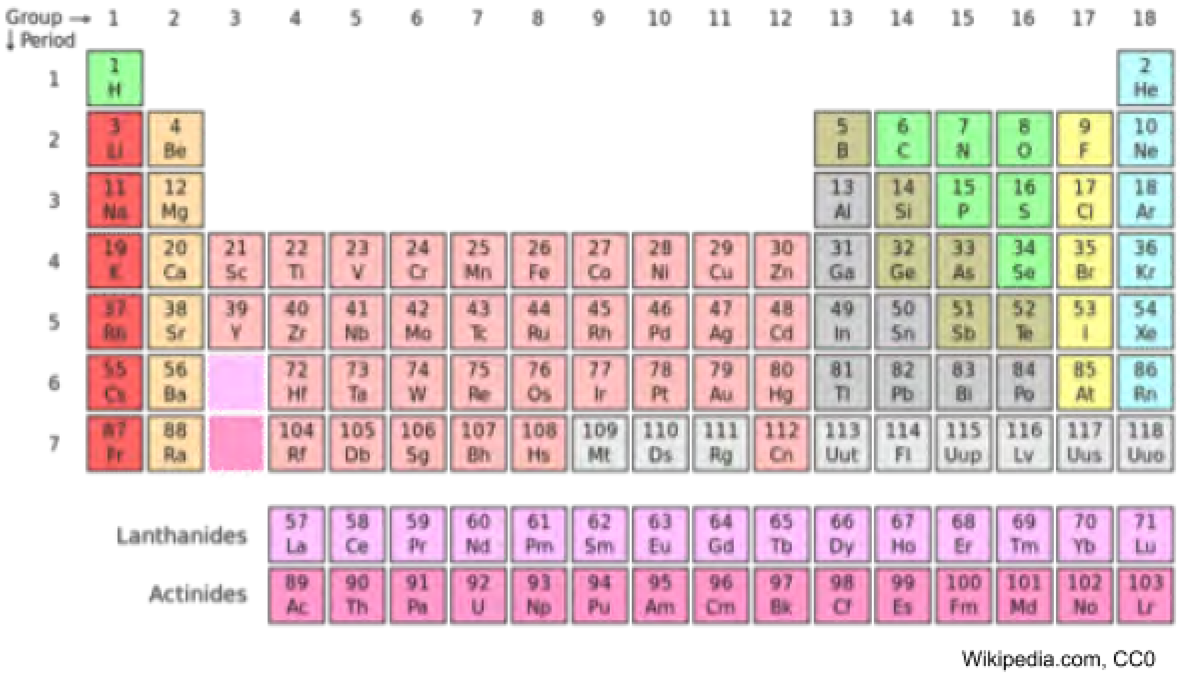
Since an atom of one element can be distinguished from an atom of another element by the number of protons in its nucleus, scientists are always interested in this number, and how this number differs between different elements. Therefore, scientists give this number a special name. An element's atomic number (the number of protons in the nucleus of an atom) is a whole number usually written above the chemical symbol of each element. The modern periodic table is based on the atomic number of elements.



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Wikipedia.com, CC0

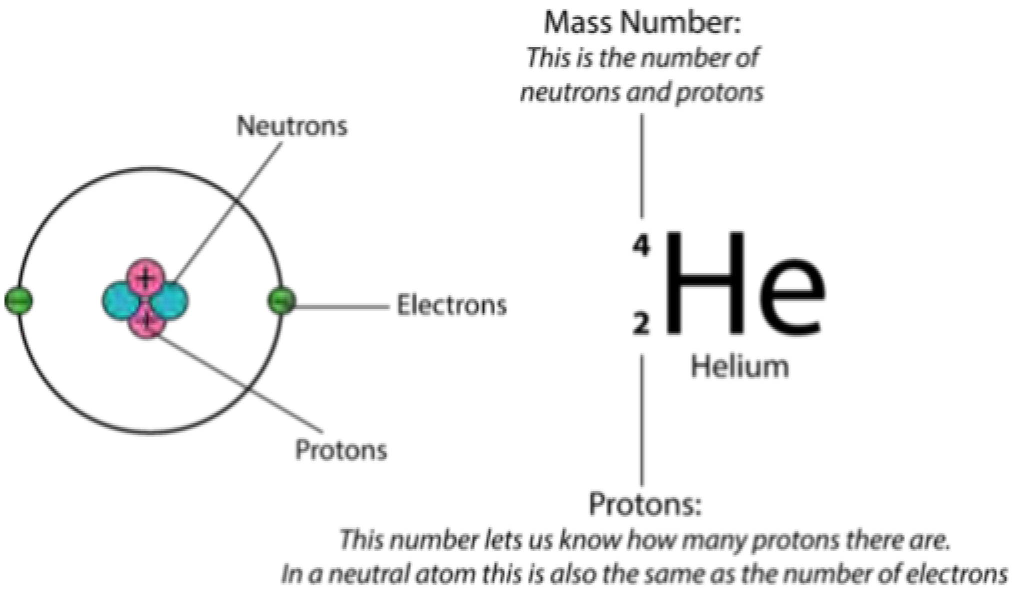
Of course, since neutral atoms have one electron for every proton, an element's atomic number also tells you how many electrons are in a neutral atom of that element. For example, hydrogen has an atomic number of 1. This means that an atom of hydrogen has one proton, and, if it's neutral, one electron as well. Gold, on the other hand, has an atomic number of 79, which means that an atom of gold has 79 protons, and, if it's neutral, and 79 electrons as well.

The mass number of an atom is the total number of protons and neutrons in its nucleus. Why do you think that the "mass number" includes protons and neutrons, but not electrons? You know that most of the mass of an atom is concentrated in its nucleus. The mass of an atom depends on the number of protons and neutrons. You have already learned that the mass of an electron is very, very small compared to the mass of either a proton or a neutron (like the mass of a penny compared to the mass of a bowling ball). Counting the number of protons and neutrons tells scientists about the total mass of an atom.

Mass number = (number of protons) + (number of neutrons)

An atom’s mass number is very easy to calculate provided you know the number of protons and neutrons in an atom.

Atomic Number



CK-12 Foundation, CC-BY-NC

Example

What is the mass number of an atom of helium that contains 2 neutrons?

Solution:

(Number of protons) = 2

(Number of neutrons) = 2

Mass number = (number of protons) + (number of neutrons) 2+2 = 4

There are two main ways in which scientists frequently show the mass number of an atom they are interested in. It is important to note that the mass number is not given on the periodic table. These two ways include writing a nuclear symbol or by giving the name of the element with the mass number written.

To write a nuclear symbol, the mass number is placed at the upper left (superscript) of the chemical symbol and the atomic number is placed at the lower left (subscript) of the symbol. The complete nuclear symbol for helium-4 is drawn above.

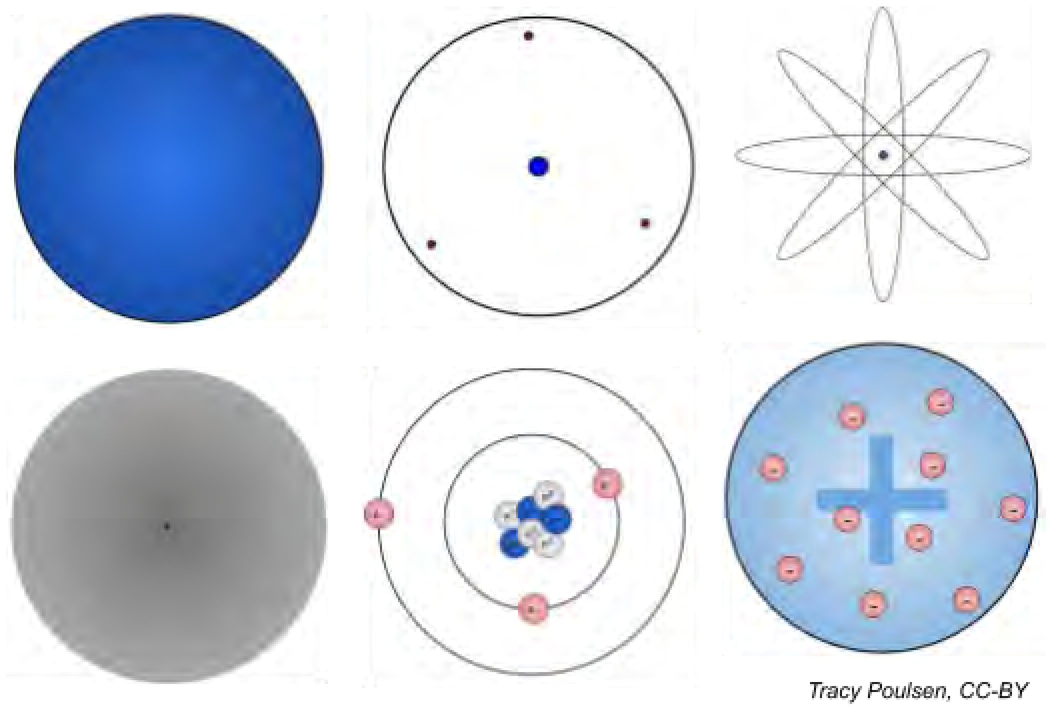
The following nuclear symbols are for a nickel nucleus with 31 neutrons and a uranium nucleus with 146 neutrons.

${}^{59}_{28}Ni$ ${}^{238}_{92}U$

In the nickel nucleus represented above, the atomic number 28 indicates the nucleus contains 28 protons, and therefore, it must contain 31 neutrons in order to have a mass number of 59. The uranium nucleus has 92 protons as do all uranium nuclei and this particular uranium nucleus has 146 neutrons.

The other way of representing these nuclei would be Nickel-59 and Uranium-238 where 59 and 238 are the mass numbers of the two atoms, respectively. Note that the mass numbers (not the number of neutrons) is given to the side of the name.

Putting It Together



Tracy Poulsen, CC-BY

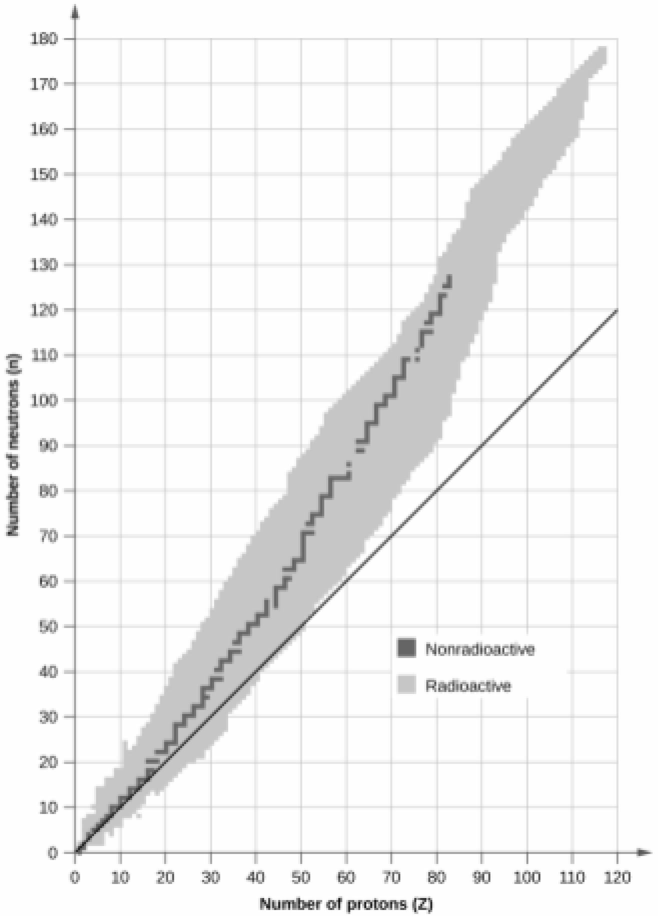
Let us revisit this phenomenon:

Look for patterns in the structure and function of these models of atoms.

1. What is the correct order of the models?
2. What evidence caused the atomic models to change over time?
3. What are the three subatomic particles? What charge does each one have?

1.2 Isotopes and Decay (Chem.1.2)

Explore this Phenomenon



21.1 Nuclear Structure and Stability by Rice University, CC-BY https://opentextbc.ca/chemistry/chapter/21-1-nuclear-structure-and-stability/

Some atoms on the chart above are stable, while others are not.

1. What subatomic particle(s) do you predict are the most important in stability?

2. Do unstable atoms follow predictable patterns?

Standard Chem.1.2

Analyze and interpret data to identify patterns in the stability of isotopes and predict likely modes of radioactive decay. Emphasize that different isotopes of the same element decay by different modes and at different rates depending on their nuclear stability. Examples of data could include band of stability charts, mass or nuclear binding energy per nucleon, or the inverse relationship between half-life and nuclear stability. (PS1.C)

As you read this section, look for patterns of stability of isotopes. What pattern is there among unstable isotopes? Predict how the nucleus will become stable.

History of Atomic Mass Determinations

As a part of his research on atoms, John Dalton determined a number of atomic weights of elements in the early 1800s. Atomic weights were the basis for the periodic table that Mendeleev developed. Originally all atomic weights were based on a comparison to hydrogen, which has an atomic weight of one. After the discovery of the proton, scientists assumed that the weight of an atom was essentially that of the protons – electrons were known to contribute almost nothing to the atomic weight of the element.

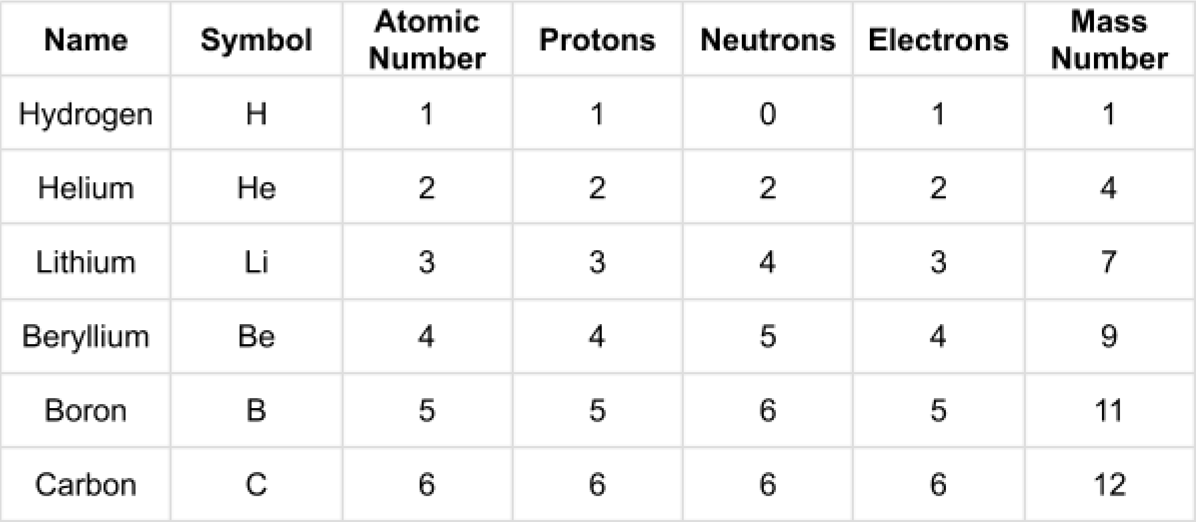
This approach worked until we learned how to determine the number of protons in an element. We then saw that the atomic weight for an element was often twice the number of protons (or more). The discovery of the neutron provided the missing part of the picture. The atomic mass is now known to be the sum of the protons and neutrons in the nucleus.

Mass Number

Rutherford showed that the vast majority of the mass of an atom is concentrated in its nucleus, which is composed of protons and neutrons. The mass number is defined as the total number of protons and neutrons in an atom. It can be calculated by adding the number of neutrons and the number of protons (atomic number) together.

Mass number = atomic number + number of neutrons

This table shows the first six elements of the periodic table.



Name	Symbol	Atomic Number	Protons	Neutrons	Electrons	Mass Number
Hydrogen	H	1	1	0	1	1
Helium	He	2	2	2	2	4
Lithium	Li	3	3	4	3	7
Beryllium	Be	4	4	5	4	9
Boron	B	5	5	6	5	11
Carbon	C	6	6	6	6	12

Consider the element helium. Its atomic number is 2, so it has two protons in its nucleus. Its nucleus also contains two neutrons. Since 2 + 2 = 4, we know that the mass number of the helium atom is 4. Finally, the helium atom also contains two electrons since the number of electrons must equal the number of protons. This example may lead you to believe that atoms have the same number of protons and neutrons, but further examination of the Table above will show that this is not the case. Lithium, for example has three protons and four neutrons, leaving it with a mass number of 7.

Knowing the mass number and the atomic number of an atom allows you to determine the number of neutrons present in the atom by subtraction.

Number of neutrons = mass number - atomic number

Atoms of the element chromium (Cr) have an atomic number of 24 and a mass number of 52. How many neutrons are in the nucleus of a chromium atom? To determine this, you would subtract as shown:

52 - 24 = 28 neutrons in a chromium atom

The composition of any atom can be illustrated with a shorthand notation using the atomic number and the mass number. Both are written before the chemical symbol, with the mass number written as a superscript and the atomic number written as a subscript. The chromium atom discussed above would be written as:

$$^{52}_{24}Cr$$

Another way to refer to a specific atom is to write the mass number of the atom after the name, separated by a hyphen. The above atom would be written as chromium-52.

Image by Simona Robová, pixabay.com, CC0

Are all the members of the football team shown above identical?

They are on the same team and are all known by the same team name, but there are individual differences among the players. We do not expect the kicker to be as big as the quarterback. The tight end is very likely to weigh less than the defensive tackle on the other side of the ball. They play as a unit, but they have different weights and heights.

Isotopes

The history of the atom is full of some of these differences. Although John Dalton stated in his atomic theory of 1804 that all atoms of an element are identical, the discovery of the neutron began to show that this assumption was not correct. The study of radioactive materials (elements that spontaneously give off particles to form new elements) by Frederick Soddy (1877-1956) gave important clues about the internal structure of atoms. His work showed that some substances with different radioactive properties and different atomic masses were in fact the same element. He coined the term isotope from the Greek roots isos (ίσος "equal") and topos (τόπος "place"). He described isotopes as, “Put colloquially, their atoms have identical outsides but different insides.” Soddy won the Nobel Prize in Chemistry in 1921 for his work.

As stated earlier, not all atoms of a given element are identical. Specifically, the number of neutrons can be variable for many elements. As an example, naturally occurring carbon exists in three forms. Each carbon atom has the same number of protons (6), which is its atomic number. Each carbon atom also contains six electrons in order to maintain electrical neutrality. However the number of neutrons varies as six, seven, or eight. Isotopes are atoms that have the same atomic number, but different mass numbers due to a change in the number of neutrons.

The three isotopes of carbon can be referred to as

carbon-12 $^{12}_{6}C$, carbon-13, $^{13}_{6}C$ and carbon-14 $^{14}_{6}C$

refers to the nucleus of a given isotope of an element. A carbon atom is one of three different nuclides. Most elements naturally consist of mixtures of isotopes. Carbon has three natural isotopes, while some heavier elements can have many more. Tin has ten stable isotopes, the most of any element.

While the presence of isotopes affects the mass of an atom, it does not affect its chemical reactivity. Chemical behavior is governed by the number of electrons and the number of protons. Carbon-13 behaves chemically in exactly the same way as the more plentiful carbon-12.

Radioactivity

What does this sign mean?

If you visit the nuclear medicine department of a large hospital, you are very likely to see the symbol shown above. The sign means that radioactive materials are present and special safety precautions need to be taken. These materials are used for diagnosis and treatment of many diseases. The people using these materials are specially trained to handle them safely. Radioactive materials can be dangerous and should be respected, but need not be feared.

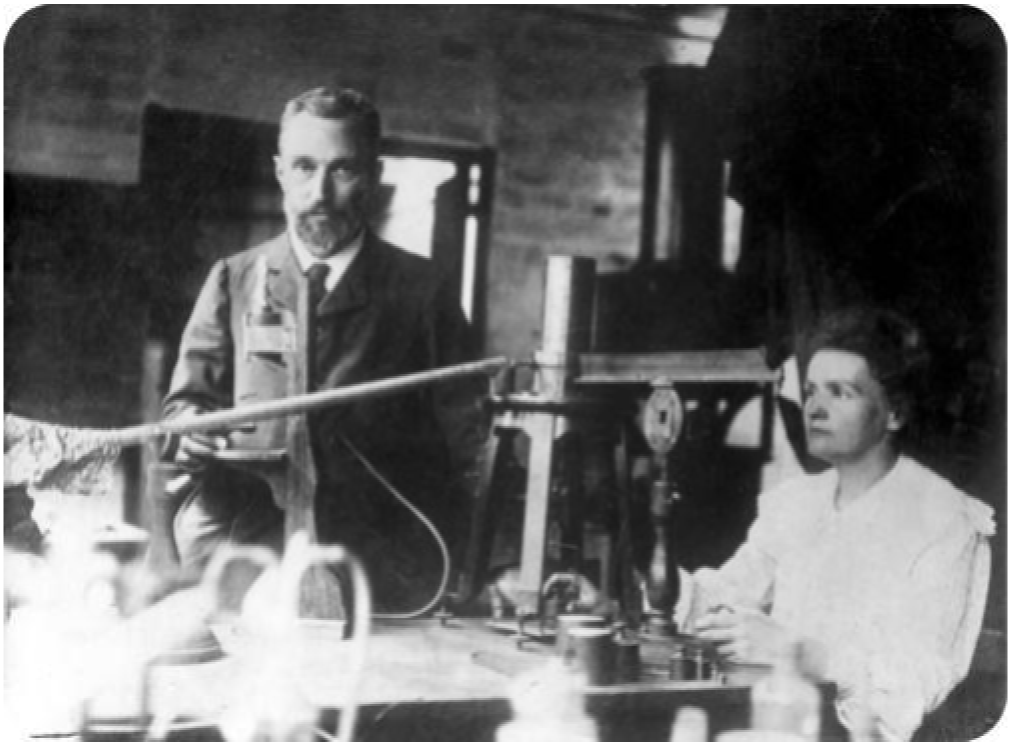
Discovery of Radioactivity

John Dalton first proposed his atomic theory in an 1804 lecture to the Royal Institution, a prestigious British scientific society. In this talk, he put forth the idea that all atoms of an element were identical and that atoms were indestructible. In a little over 100 years, both of these ideas were shown to be incorrect.

In 1919, studies on atomic weights led Francis Aston (1877-1925) to the conclusion that some elements with different atomic weights were actually the same element in different isotope forms. Aston used a mass spectrograph to separate isotopes of different elements. He won the Nobel Prize in Chemistry for this work in 1922.

Natural Radioactivity

Pierre and Marie Curie studied the properties of uranium salts with the express purpose of identifying the details of these emissions. They were the first to coin the term "radioactivity," meaning the spontaneous emission of radiation in the form of particles or high energy photons resulting from a nuclear reaction. The major contributions to the work came from Marie who showed that the amount of radioactivity present was due to the amount of a specific element and not due to some chemical reaction. She discovered the element polonium and named it after her native Poland. Madame Curie shared the 1903 Nobel Prize in Physics with her husband Pierre and Henri Becquerel. She won the Nobel Prize in Chemistry in 1911.



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Pierre and Marie Curie in their lab.

Ernest Rutherford, a later researcher, was able to show there are three different types of radioactive emissions. These emission types differed in terms of mass, charge, and their ability to penetrate materials. He designated them simply as alpha (α) emissions, beta (β) emissions, and gamma (γ) emissions.

Radioactivity involves the spontaneous emission of material and/or energy from the nucleus of an atom. The most common radioactive atoms have high atomic numbers and contain a large excess of neutrons.

Trends in Type of Radioactive Decay

This section is adapted from Radioactive Decay by Rice University, , CC-BY. To view the original book go to: https://cnx.org/contents/mrt82dCz@2/Radioactive-Decay

Alpha (α) decay is the emission of an α particle from the nucleus. For example, polonium-210 undergoes α decay:

$$^{210}_{84}\mathrm{Po} \longrightarrow {}^{4}_{2}\alpha + {}^{206}_{82}\mathrm{Pb}$$

Alpha decay occurs primarily in heavy nuclei ($A > 200$, $Z > 83$). Because the loss of an α particle gives a daughter nuclide with a mass number four units smaller and an atomic number two units smaller than those of the parent nuclide, the daughter nuclide has a larger n:p ratio than the parent nuclide. If the parent nuclide undergoing α decay lies below the band of stability (refer to [link]), the daughter nuclide will lie closer to the band.

Beta (β) decay is the emission of an electron from the nucleus. Iodine-131 is an example of a nuclide that undergoes β decay:

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{0}_{-1}\beta + {}^{131}_{54}\mathrm{Xe}$$

Beta decay, which can be thought of as the conversion of a neutron into a proton and a β particle, is observed in nuclides with a large n:p ratio. The beta particle (electron) emitted is from the atomic nucleus and is not one of the electrons surrounding the nucleus. Such nuclei lie above the band of stability. Emission of an electron does not change the mass number of the nuclide but does increase the number of its protons and decrease the number of its neutrons. Consequently, the n:p ratio is decreased, and the daughter nuclide lies closer to the band of stability than did the parent nuclide.

Gamma emission (γ emission) is observed when a nuclide is formed in an excited state and then decays to its ground state with the emission of a γ ray, a quantum of high-energy electromagnetic radiation. The presence of a nucleus in an excited state is often indicated by an asterisk (*). Cobalt-60 emits γ radiation and is used in many applications including cancer treatment:

$$^{60}_{27}\text{Co}^{*} \longrightarrow {}^{0}_{0}\gamma + {}^{60}_{27}\text{Co}$$

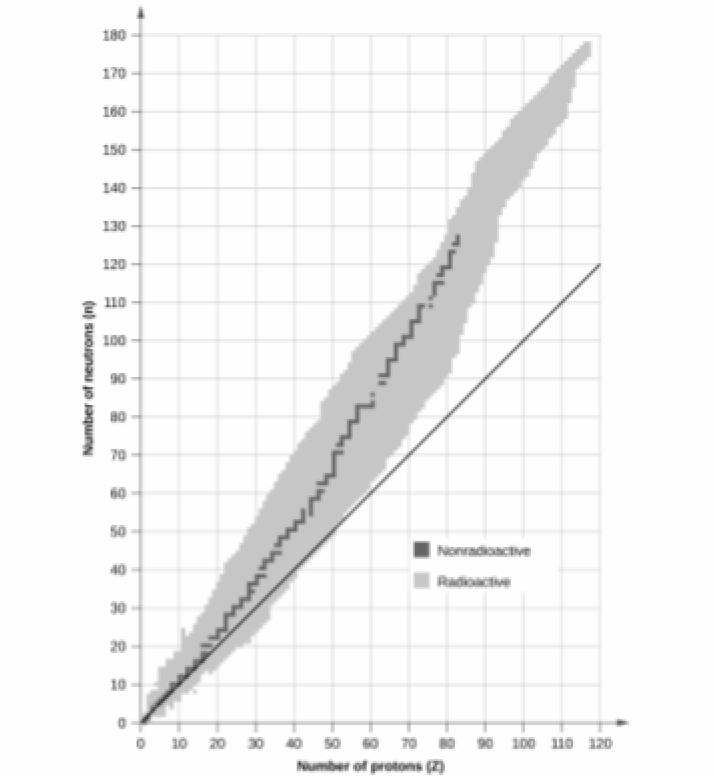
There is no change in mass number or atomic number during the emission of a γ ray unless the γ emission accompanies one of the other modes of decay.

Positron emission (β+ decay) is the emission of a positron from the nucleus. Oxygen-15 is an example of a nuclide that undergoes positron emission:

$$^{15}_{8}\text{O} \longrightarrow {}^{0}_{+1}\beta + {}^{15}_{7}\text{N}$$

Positron emission is observed for nuclides in which the n:p ratio is low. These nuclides lie below the band of stability. Positron decay is the conversion of a proton into a neutron with the emission of a positron. The n:p ratio increases, and the daughter nuclide lies closer to the band of stability than did the parent nuclide.

Putting It Together



21.1 Nuclear Structure and Stability by Rice University, CC-BY https://opentextbc.ca/chemistry/chapter/21-1-nuclear-structure-and-stability/

Let us revisit the phenomenon:

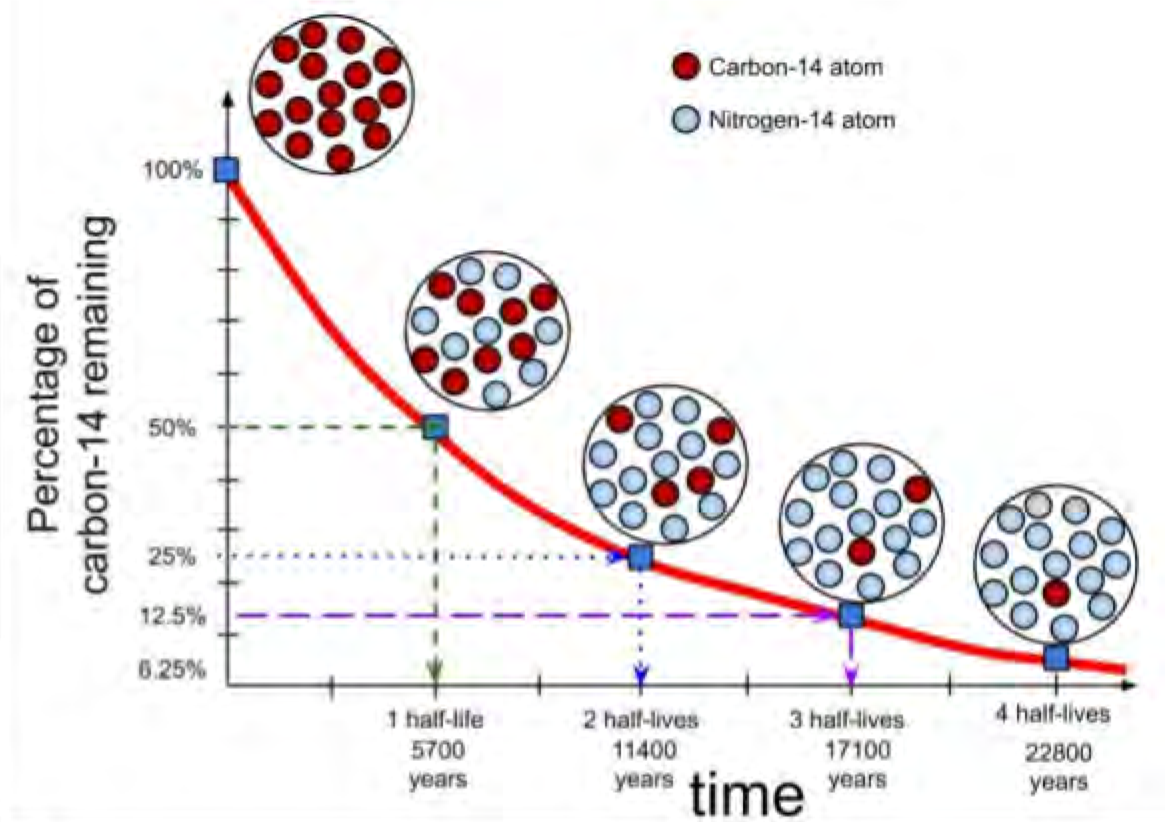
1. Does the band of nonradioactive elements match up with the straight line that represents a 1:1 ratio of protons to neutrons? Why would that happen?

2. How many protons are in the last nonradioactive element? Are there elements that have a larger number of protons than that?

3. Which would be the radioactive and nonradioactive isotopes of ^{64}Zn and ^{60}Zn? Explain how you know.

1.3 Half-life (Chem.1.3)

Explore this Phenomenon



Tracy Poulsen, CC-BY

The graph above shows the half-life of carbon-14.

1. What is happening to the amount of carbon-14 isotope over time?
2. What does the exponential curve in the graph represent?

Standard Chem.1.3

Use mathematics and computational thinking to relate the rates of change in quantities of radioactive isotopes through radioactive decay (alpha, beta, and positron) to ages of materials or persistence in the environment. Emphasize a conceptual understanding of half-life. Examples could include radiocarbon dating, nuclear waste management, or nuclear medicine. (PS1.C)

While reading this section discover why and how the nucleus of an atom changes. What is the rate at which it changes?

Types of Radioactive Decay

In ordinary chemical reactions and processes, atoms of one element never change into different elements. The protons in the nucleus of an atom determines the identity of that element. Most chemical changes are related to changes with the electrons of atoms. In these nuclear decay processes the nucleus, which contains protons and neutrons, is changing. All nuclei with 84 or more protons are radioactive and elements with less than 84 protons have both stable and unstable isotopes. All these elements can go through nuclear changes and turn into different elements.

Isotopes of elements that have an unstable ratio of protons to neutrons in the nucleus of atoms tend to break down and release energy in the form of radiation like alpha, beta, and positron emissions. Oxygen isotopes all have 8 protons but Oxygen-16 has 8 neutrons while Oxygen-17 has 9 neutrons. Oxygen-17 will be unstable, and release radiation. Another example are the isotopes of Carbon, Carbon-12 and Carbon-14. Carbon-14 has more neutrons than Carbon-12 and is therefore, unstable.

Nuclear Decay Processes

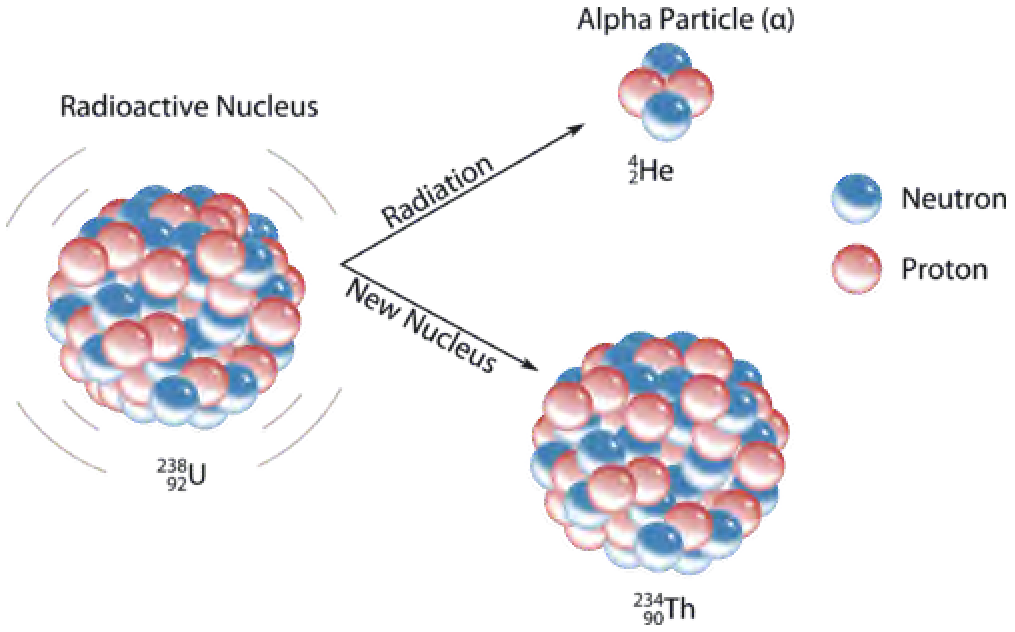
Radioactive decay involves the emission of a particle and/or energy as one atom changes into another. In most instances, the atom changes its identity to become a new element. Discussed here are three types of emissions that occur.

Alpha Emission

Alpha (α) decay involves the release of helium ions from the nucleus of an atom. This ion consists of two protons and two neutrons and has a 2+ charge. Release of an α-particle produces a new atom that has an atomic number two less than the original atom and an atomic mass that is four less. A typical alpha decay reaction is the conversion of uranium-238 to thorium:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha^{+}$$

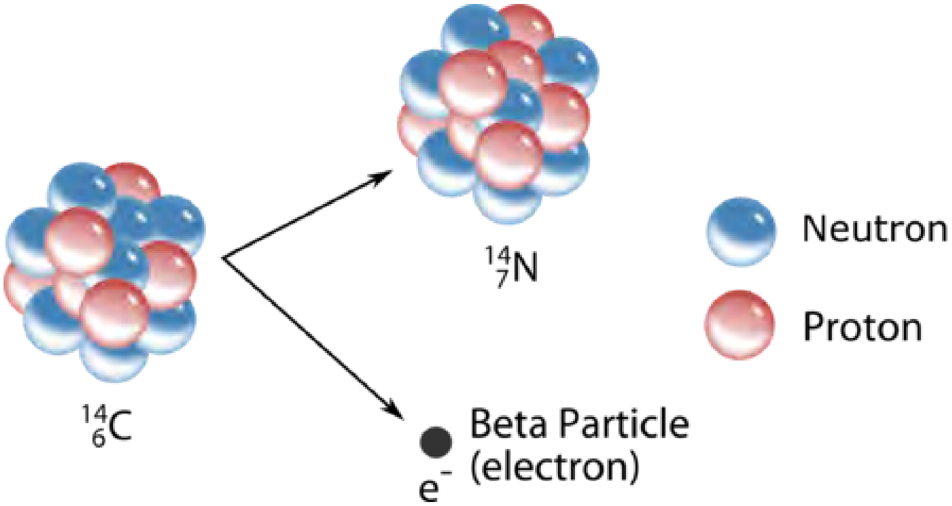
We see a decrease of two in the atomic number (uranium to thorium) and a decrease of four in the atomic mass (238 to 234). Usually the emission is not written with atomic number and mass indicated since it is a common particle whose properties should be memorized. Quite often the alpha emission is accompanied by gamma (γ) radiation, a form of energy release. Many of the largest elements in the periodic table are alpha-emitters.



Emission of an alpha particle from the nucleus.

Beta Emission

Beta (β) decay is a more complicated process. Unlike the α-emission, which simply expels a particle, the β-emission involves the transformation of a neutron in the nucleus to a proton and an electron. The electron is then ejected from the nucleus. In the process, the atomic number increases by one while the atomic mass stays the same. As is the case with α-emissions, β-emissions are often accompanied by γ-radiation.



Beta emission.

https://flexbooks.ck12.org/cbook/ck-12-chemistry-flexbook-2.0/section/24.2/primary/lesson/nuclear-decay-processes-chem

A typical beta decay process involves carbon-14, often used in radioactive dating techniques. The reaction forms nitrogen-14 and an electron:

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} $$

Again, the beta emission is usually simply indicated by the Greek letter β; memorization of the process is necessary in order to follow nuclear calculations in which the Greek letter β without further notation.

Positron Emission

A positron is a positive electron (a form of antimatter). This rare type of emission occurs when a proton is converted to a neutron and a positron in the nucleus, with ejection of the positron. The atomic number will decrease by one while the atomic weight does not change. A positron is often designated by β^+.

Carbon-11 emits a positron to become boron-11:

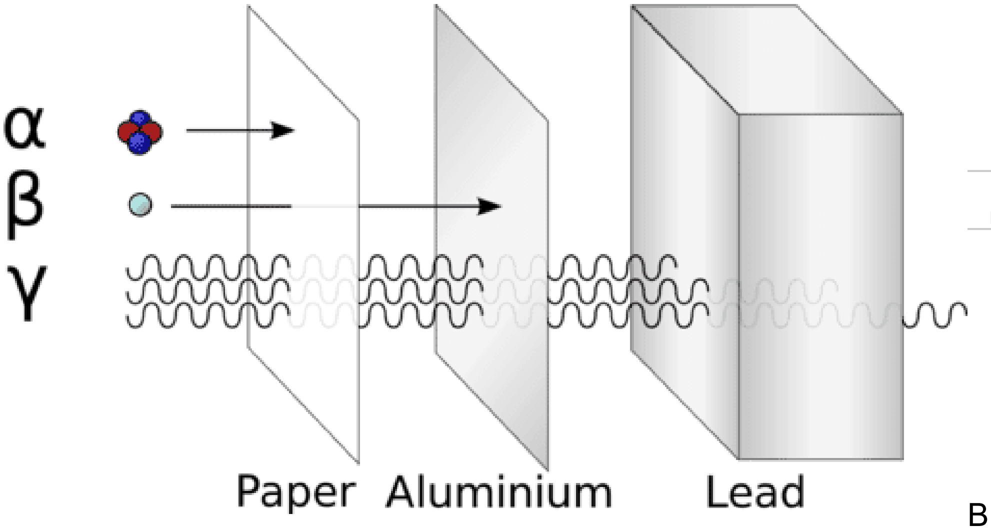
$$ {}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\beta $$

Gamma Emission

Gamma (γ) radiation is simply energy. It may be released by itself or more commonly in association with other radiation events. There is no change of atomic number or atomic mass in a simple γ-emission. Often, an isotope may produce γ-radiation as a result of a transition in a metastable isotope. This type of isotope may just “settle,” with a shifting of particles in the nucleus. The composition of the atom is not altered, but the nucleus could be considered more “comfortable” after the shift. This shift increases the stability of the isotope from the energetically unstable (or “metastable”) isotope to a more stable form of the nucleus.

Penetrating Ability of Emissions

The various emissions will differ considerably in their ability to go through matter, known as their penetrating ability. The α-particle has the least penetrating power since it is the largest and slowest emission. It can be blocked by a sheet of paper or a human hand. Beta particles are more penetrating than alpha particles, but can be stopped by a thin sheet of aluminum. Of the three basic types of emissions, gamma particles are the most penetrating. A thick lead shield is required to stop gamma emissions. Positrons represent a special case in that they annihilate when they come in contact with electrons. The collision of a positron and an electron results in the formation of two gamma emissions that go 180 degrees away from each other.



Penetrating ability of radioactive emissions.

Blocking of alpha particles can easily be accomplished by as little as 10 mm plastic or paper. Beta emissions represent a somewhat different situation. The negative charge on a beta particle has the potential for activating the element being used to block the radiation. Lead and tungsten are large atoms with many protons and neutrons in their nuclei. While the beta electron may be blocked, the target material could become irradiated in the process.

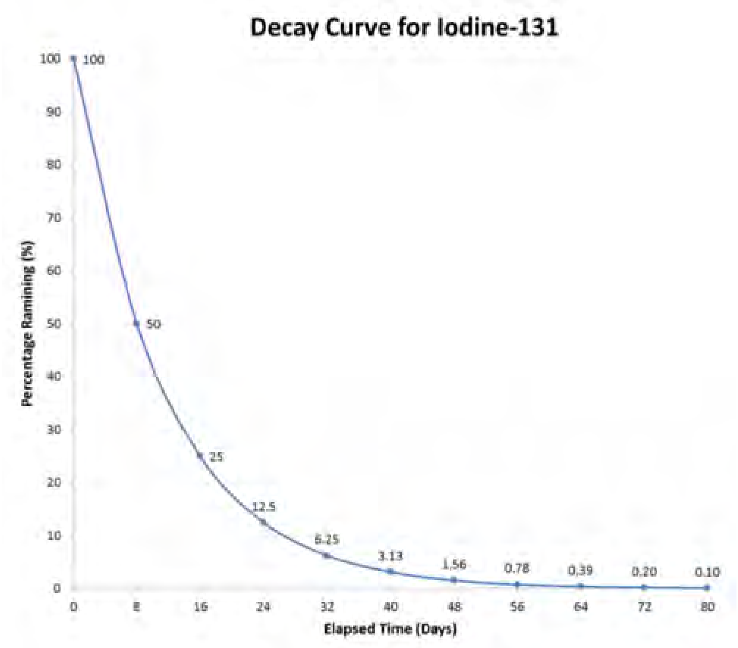
High-density materials are much more effective protection against gamma emissions than low-density ones. Gamma rays are usually blocked effectively by lead shielding. The thickness of the shielding will determine the effectiveness of the protection offered by the lead.

We’re putting it where?

Uranium isotopes produce plutonium-239 as a decay product. The plutonium can be used in nuclear weapons and is a power source for nuclear reactors, which generate electricity. This isotope has a half-life of 24,100 years, causing concern in regions where radioactive plutonium has accumulated and is stored. At some storage sites, the waste is slowly leaking into the groundwater and contaminating nearby rivers. The 24,100 year half-life means that it will be with us for a very long time.

Half-Life

Radioactive materials lose some of their activity each time a decay event occurs. This loss of activity can be estimated by determining the half-life of an isotope. The half-life is defined as that period of time needed for one-half of a given quantity of a substance to undergo a change. For a radioisotope, every time a decay event occurs, a count is detected on the Geiger counter or other measuring device. A specific isotope might have a total count of 30,000 cpm. In one hour, the count could be 15,000 cpm (half the original count). So the half-life of that isotope is one hour. Some isotopes have long half-lives – the half-life of U-234 is 245,000 years. Other isotopes have shorter half-lives. I-131, used in thyroid scans, has a half-life of 8.02 days.



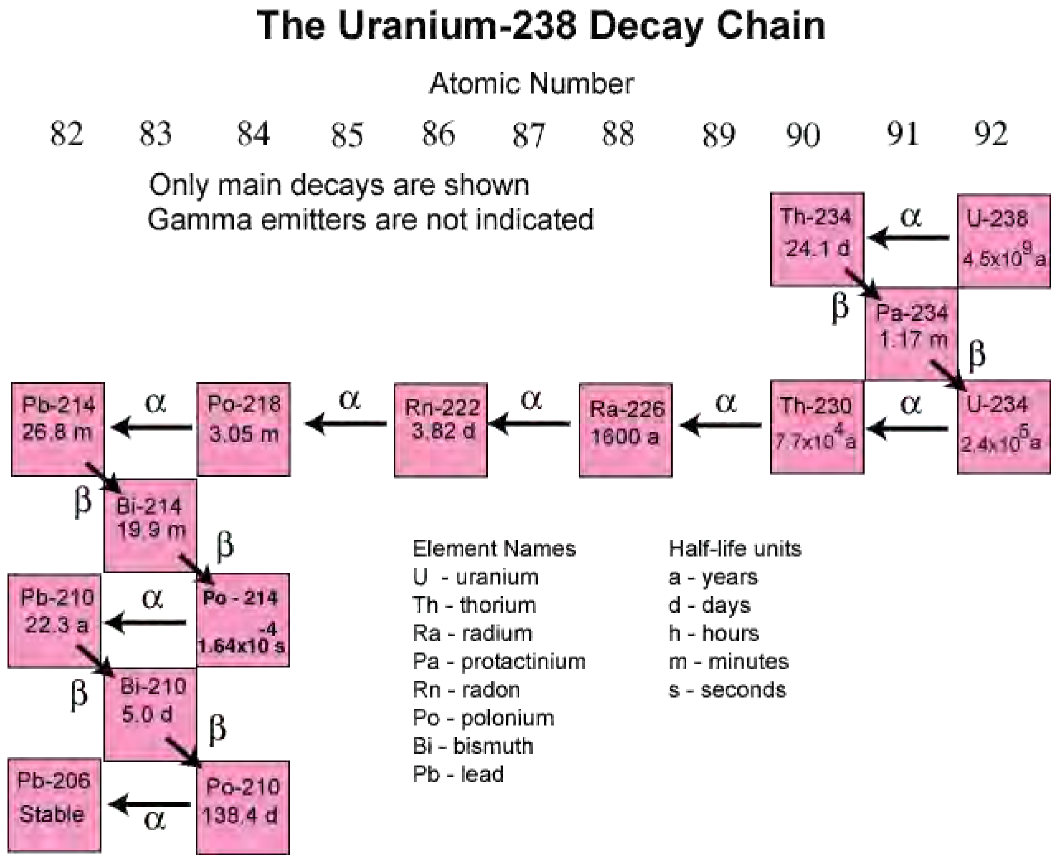
This graph illustrates a typical decay curve for a radioactive material. The activity decreases by one-half during each succeeding half-life.

Typical radioactive decay curve.

Half-lives of different elements vary considerably, as shown in Table below:

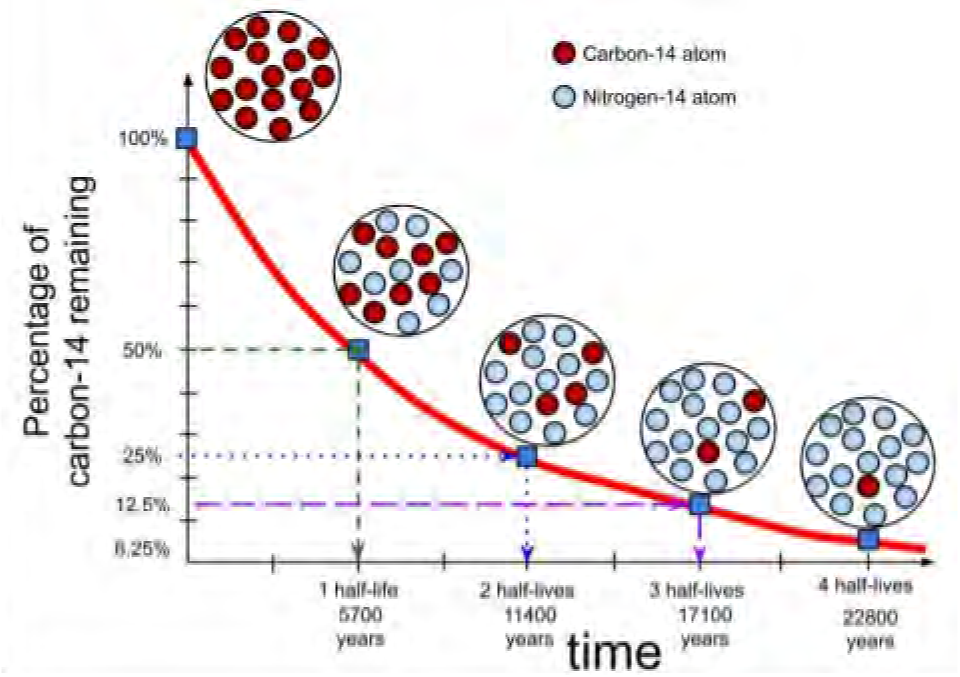
Isotope	Decay Mode	Half-Life
Cobalt-60	beta	5.3 years
Neptunium-237	alpha	2.1 million years
Polonium-214	alpha	0.00016 seconds
Radium-224	alpha	3.7 days
Tritium (H-3)	beta	12 years

We have talked about the activity and decay of individual isotopes. In the real world, there is a decay chain that takes place until a stable end-product is produced. For U-238, the chain is a long one, with a mix of isotopes having very different half-lives. The end of the chain resides in lead, a stable element that does not decay further.



Decay of uranium to stable end-product.

Putting It Together



Tracy Poulsen, CC-BY

Let us revisit this phenomenon:

1. How long is the half-life of carbon-14?

2. What percent of carbon-14 is left after 3 half-lives?

1.4 Nuclear Reactions (Chem.1.4)

Explore this Phenomenon

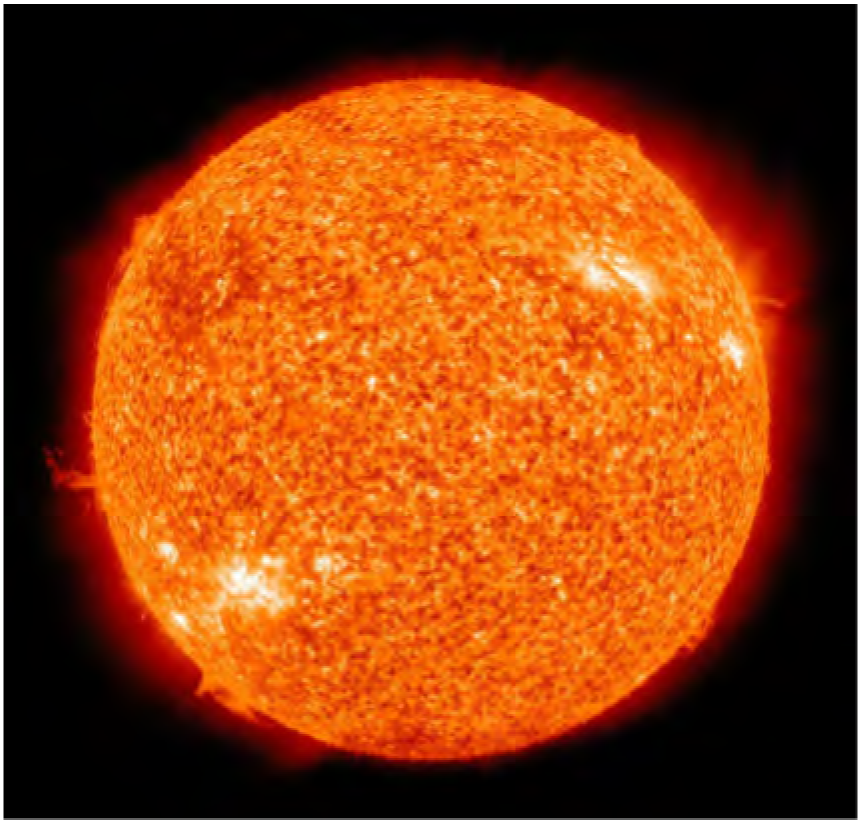


Image by WikiImages, pixabay.com, CC0

Stars produce large amounts of energy.

1. How do stars produce energy?
2. Can stars “run out” of their fuel?

Standard Chem.1.4

Construct an explanation about how fusion can form new elements with greater or lesser nuclear stability. Emphasize the nuclear binding energy, with the conceptual understanding that when fusion of elements results in a more stable nucleus, large quantities of energy are released, and when fusion results in a less stable nucleus, large quantities of energy are required. Examples could include the building up of elements in the universe starting with hydrogen to form heavier elements, the composition of stars, or supernovae producing heavy elements. (PS1.C, ESS1.A)

As you go through the section look for how fusion can form new elements with greater or lesser nuclear stability. What makes a nucleus stable or unstable?

Forces in the Nucleus

A carbon nucleus of ^{12}C (for instance) contains 6 protons and 6 neutrons. The protons are all positively charged and repel each other: they nevertheless stick together, showing the existence of another force—a nuclear attraction, the strong nuclear force, which overcomes electric repulsion at very close range. Hardly any effect of this force is observed outside the nucleus, so it must have a much stronger dependence on distance—it is a short range force. The same force is also found to pull neutrons together, or neutrons and protons.

Nuclear Fusion

In contrast to nuclear fission, which results in smaller isotopes being formed from larger ones, the goal of nuclear fusion is to produce larger materials from the collision of smaller atoms. The forcing of the smaller atoms together results in tighter packing and the release of energy. As seen in the Figure below, energy is released in the formation of the larger atom, helium (He) from the fusion of hydrogen-2 and hydrogen-3 as well as from the expulsion of a neutron.

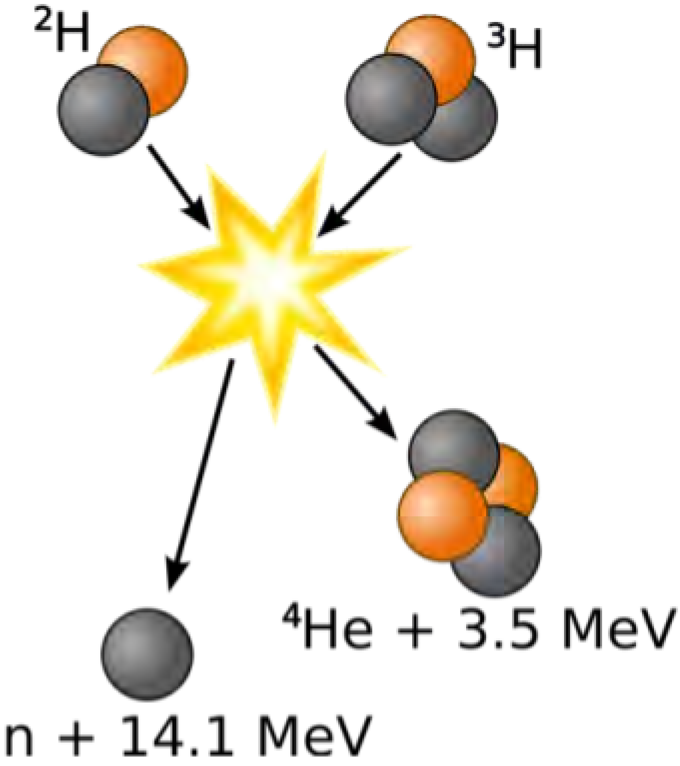


Image by Wykis, wikimedia.org, CC0

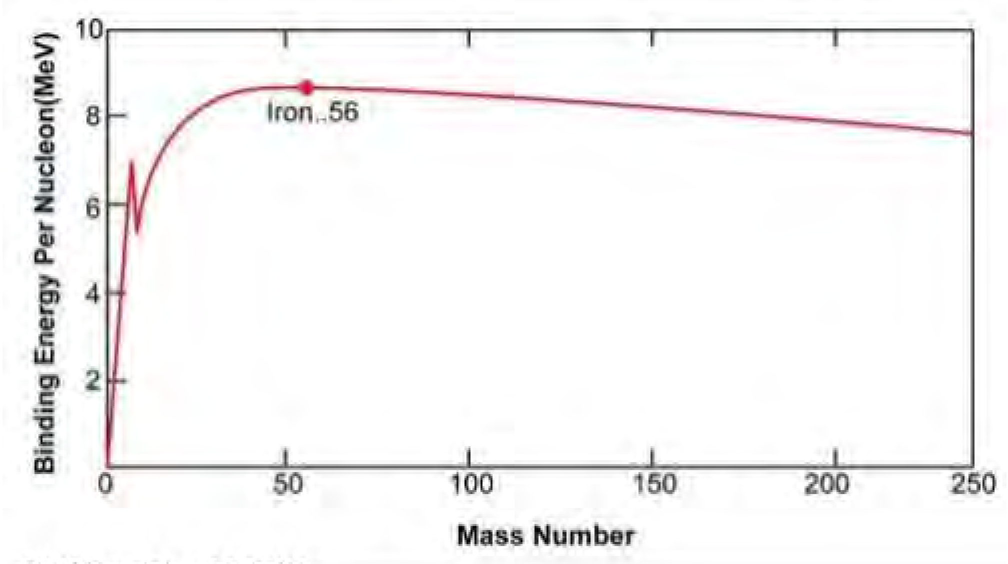
Nuclear fusion reaction between deuterium and tritium.

This release of energy is what drives research on fusion reactors today. If such a reaction could be accomplished efficiently on Earth, it could provide a clean source of nuclear energy. Unlike fission reactions, nuclear fusion does not produce radioactive products that represent hazards to living systems.

Nuclear fusion reactions in the laboratory have been extraordinarily difficult to achieve. Extremely high temperatures (millions of degrees) are required. Methods must be developed to force the atoms together and hold them together long enough to react. The neutrons released during the fusion reactions can interact with atoms in the reactor and convert them to radioactive materials. There has been some success in the field of nuclear fusion reactions, but the journey to feasible fusion power is still a long and uncertain one.

The Curve of Binding Energy

In the main isotopes of light nuclei, such as carbon, nitrogen and oxygen, the number of neutrons and of protons is indeed equal. However, as one moves to heavier nuclei, the disruptive energy of electric repulsion increases, because electric forces have a long range and each proton is repelled by all other protons in the nucleus. In contrast, the strong nuclear attraction between those protons increases only moderately, since the force has a short range and affects mainly immediately neighboring protons.



CK-12 Foundation, CC-BY-NC

The Binding Energy of Nuclei

The net binding energy of a nucleus is that of the nuclear attraction, minus the energy of the repulsive electric force. As nuclei get heavier than helium, their net binding energy per nucleon (deduced from the difference in mass between the nucleus and the sum of masses of component nucleons) grows more and more slowly, reaching its peak at iron. As nucleons are added, the total nuclear binding energy always increases—but the total energy of electric forces (positive protons repelling other protons) also increases, and past iron, the second increase outweighs the first. One may say ^{56}Fe is the most tightly bound nucleus.

To reduce the energy of the repulsive electric force, the weak interaction allows the number of neutrons to exceed that of protons—for instance, in the main isotope of iron, 26 protons, but 30 neutrons. Of course, isotopes also exist in which the number of neutrons differs, but if these are too far from stability, after some time nucleons convert to a more stable isotope by beta emission radioactivity—protons turn into neutrons by emitting a positron, the positive counterpart of the electron, or neutrons become protons by emitting electrons (neutrinos are also emitted in these processes).

Among the heaviest nuclei, containing 200 or more nucleons, electric forces may be so destabilizing that entire chunks of the nucleus get ejected, usually in combinations of 2 protons and 2 neutrons (alpha particles, actually fast helium nuclei), which are extremely stable.

The curve of binding energy (figure above) plots binding energy per nucleon against atomic mass. It has its main peak at iron and then slowly decreases again, and also a narrow isolated peak at helium, which as noted is very stable. The heaviest nuclei in nature, uranium ^{238}U, are unstable, but having a lifetime of 4.5 billion years, close to the age of the Earth, they are still relatively abundant; they (and other nuclei heavier than iron) may have formed in a supernova explosion preceding the formation of the solar system. The most common isotope of thorium, ^{232}Th, also undergoes α particle emission, and its half-life (time over which half a number of atoms decays) is even longer, by several times. In each of these, radioactive decay produces daughter isotopes, that are also unstable, starting a chain of decays that ends in some stable isotope of lead.

How are elements born?

A number of reactions take place in the sun that cannot be duplicated on Earth. Some of these reactions involve the formation of large elements from smaller ones. So far, we have only been able to observe the formation of very small elements here on Earth. The reaction sequence observed appears to be the following: Hydrogen-1 atoms collide to form the larger hydrogen isotopes, hydrogen-2 (deuterium) and hydrogen-3 (tritium). In the process, positrons and gamma rays are formed. The positrons will collide with any available electrons and annihilate, producing more gamma rays. In the process, tremendous amounts of energy are produced to keep us warm and continue supplying reactions.

The binding energy of helium is a significant energy source of the Sun and of most stars. The Sun has plenty of hydrogen, whose nucleus is a single proton, and energy is released when 4 protons combine into a helium nucleus, a process in which two of them are also converted to neutrons.

The conversion of protons into neutrons is the result of another nuclear force, known as the weak force. The weak force also has a short range, but is much weaker than the strong force. The weak force tries to make the number of neutrons and protons in the nucleus equal; these two particles are closely related and are sometimes collectively known as nucleons.

The protons combine to helium only if they have enough velocity to overcome each other's repulsion and get within range of the strong nuclear attraction, which means they must form a very hot gas. Hydrogen hot enough for combining to helium requires an enormous pressure to keep it confined, but suitable conditions exist in the central regions of the Sun (core), where such pressure is provided by the enormous weight of the layers above the core, created by the Sun's strong gravity. The process of combining protons to form helium is an example of nuclear fusion.

Elements past iron on the periodic table cannot be formed during the fusion happening during the life of a star. Elements past iron require a supernova to be formed. This is why there is a drop in abundance in elements after iron.

Putting It Together

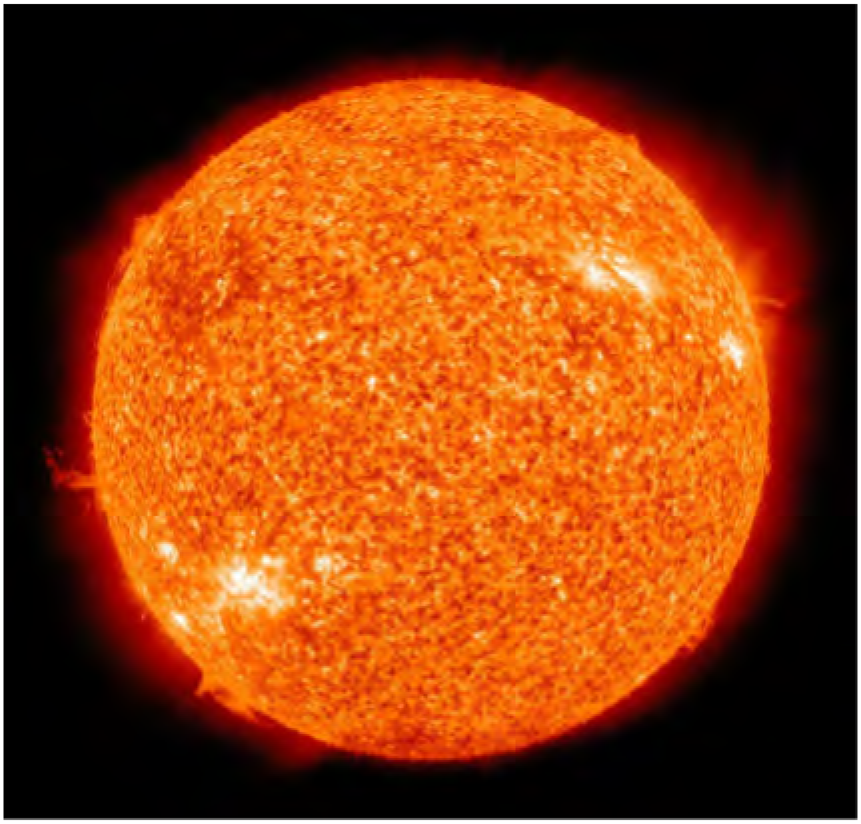


Image by WikiImages, pixabay.com, CC0

Let us revisit this phenomenon:

Stars produce large amounts of energy.

1. Using your understanding of nuclear reactions, explain how stars produce energy.

2. How is the way that stars produce energy connected to nuclear binding energy?

1.5 Periodic Table (Chem.1.5)

Explore this Phenomenon

Image from US Department of Energy, Public domain

This is a picture of about 3 pounds of sodium reacting with water. Sodium is an alkali metal.

1. Would you expect the other alkali metals to react the same way?
2. Would you expect the elements in the same row to react the same way?

Standard Chem.1.5

Use the periodic table as **a mode**l to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms. Emphasize conceptual understanding of trends and patterns. Examples could include trends in ionization energy, atomic radius, or electronegativity. Examples of properties for main group elements could include general reactivity, bonding type, or ion formation. (PS1.A)

As you read the following section, identify patterns of the periodic table such as atomic radius, amount of protons, neutrons, and electrons, and/or physical properties.

The Periodic Law

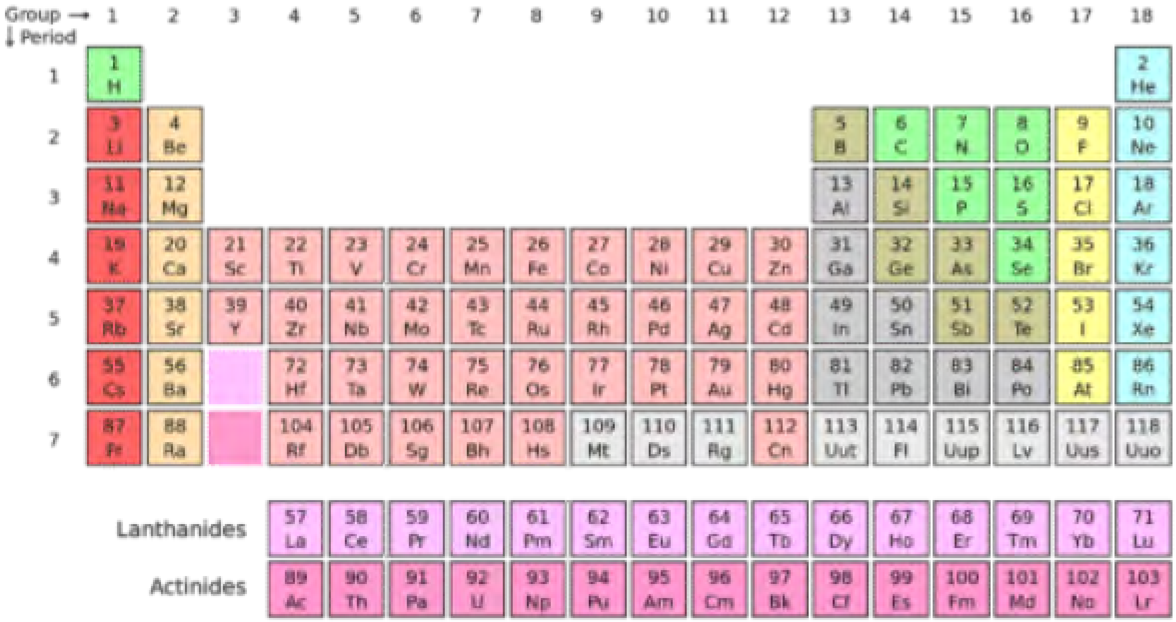
The first periodic table was developed by Dmitri Mendeleev, organized by atomic weight. When Mendeleev put his periodic table together, nobody knew about the existence of the nucleus. It was not until 1911 that Rutherford conducted his gold foil experiment that demonstrated the presence of the nucleus in the atom. Just two years later, in 1913, English physicist Henry Moseley (1887-1915) examined x-ray spectra of a number of chemical elements. He would shoot X-rays through crystals of the element and study the wavelengths of the radiation he detected. Moseley found that there was a relationship between wavelength and atomic number. His results led to the definition of atomic number as the number of protons contained in the nucleus of each atom. He then realized that the elements of the periodic table should be arranged in order of increasing atomic number rather than increasing atomic mass.

When ordered by atomic number, the discrepancies within Mendeleev's table disappeared. Tellurium has an atomic number of 52, while iodine has an atomic number of 53. So even though tellurium does indeed have a greater atomic mass than iodine, it is properly placed before iodine in the periodic table. Mendeleev and Moseley are credited with being most responsible for the modern periodic law: When elements are arranged in order of increasing atomic number, there is a periodic repetition of their chemical and physical properties. The result is the periodic table as we know it today. Each new horizontal row of the periodic table corresponds to the beginning of a new period because a new principal energy level is being filled with electrons. Elements with similar chemical properties appear at regular intervals, within the vertical columns called groups.

The Modern Periodic Table

The periodic table has undergone extensive changes in the time since it was originally developed by Mendeleev and Moseley. Many new elements have been discovered, while others have been artificially synthesized. Each fits properly into a group of elements with similar properties. The periodic table is an arrangement of the elements in order of their atomic numbers so that elements with similar properties appear in the same vertical column or group.

The figure below shows the most commonly used form of the periodic table. Each square shows the chemical symbol of the element along with its name. Notice that several of the symbols seem to be unrelated to the name of the element: Fe for iron, Pb for lead, etc. Most of these are the elements that have been known since ancient times and have symbols based on their Latin names. The atomic number of each element is written above the symbol.



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Periodic table from wikipedia, CC0

A period is a horizontal row of the periodic table. There are seven periods in the periodic table, with each one beginning at the far left. A new period begins when a new principal energy level begins filling with electrons. Period 1 has only two elements (hydrogen and helium), while periods 2 and 3 have 8 elements. Periods 4 and 5 have 18 elements. Periods 6 and 7 have 32 elements because the two bottom rows that are separated from the rest of the table belong to those periods. They are pulled out in order to make the table itself fit more easily onto a single page.

A group is a vertical column of the periodic table, based on the organization of the outer shell electrons. There are a total of 18 groups. There are two different numbering systems that are commonly used to designate groups and you should be familiar with both. The traditional system used in the United States involves the use of the letters A and B. The first two groups are 1A and 2A, while the last six groups are 3A through 8A. The middle groups use B in their titles. Unfortunately, there was a slightly different system in place in Europe. To eliminate confusion the International Union of Pure and Applied Chemistry (IUPAC) decided that the official system for numbering groups would be a simple 1 through 18 from left to right. Many periodic tables show both systems simultaneously.

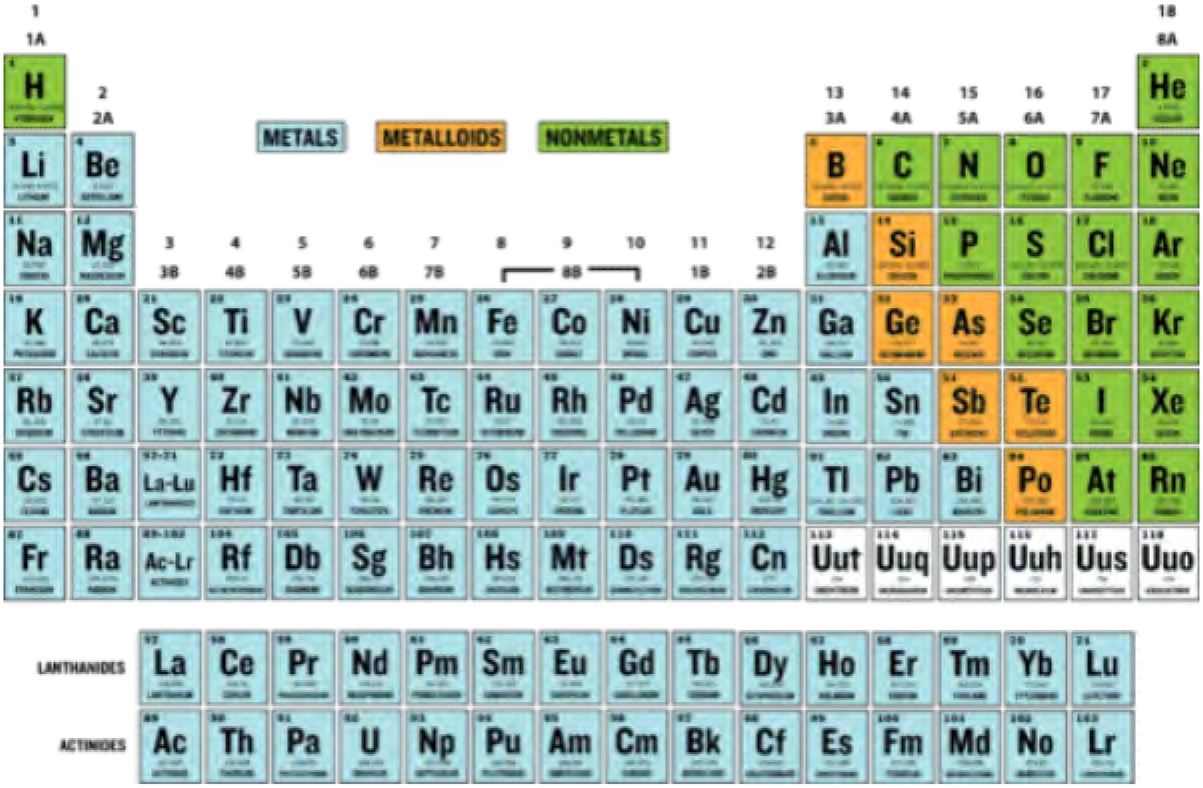
Can you guess what types of metal screws are made of?

Screws come in all sizes and shapes. They are all (well, almost all) made of some kind of metal. But they have differences in size, shape, and type of metal. Physical characteristics also differ. Some screws are long, and others are short. One screw may have a flat-head slot while another screw may have a Phillips-head. Some of the screws in the picture below are used to fasten things together, and others are used to hang heavy objects on a wall.

Chemists classify materials in many ways. We can sort elements on the basis of their electron arrangements. The way the electrons are distributed determines the chemical properties of the element. Another way is to classify elements based on physical properties. Some common physical properties are color, volume, and density. Other properties that allow us to sort on the basis of behavior are conduction of heat and electricity, malleability (the ability to be hammered into very thin sheets), ductility (the ability to be pulled into thin wires), melting point, and boiling point. Three broad classes of elements based on physical properties are metals, nonmetals, and metalloids.

Metals

A metal is an element that is a good conductor of heat and electricity. Metals are also malleable, which means that they can be hammered into very thin sheets without breaking. They are ductile, which means that they can be drawn into wires. When a fresh surface of any metal is exposed, it will be very shiny because it reflects light well. This is called luster. All metals are solid at room temperature with the exception of mercury (Hg), which is a liquid. Melting points of metals display a very wide variance. The melting point of mercury is -39°C, while the highest melting metal is tungsten (W), with a melting point of 3422°C. The elements in blue in the periodic table below are metals. About 80 percent of the elements are metals.



1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo

LANTHANIDES	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
ACTINIDES	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA

Gold has been used by many civilizations for making jewelry (see Figure below). This metal is soft and easily shaped into a variety of items. Since gold is very valuable and often used as currency, gold jewelry has also often represented wealth.

Gold jewelry.

Gold rings and beads with granulated decoration by Dorieo, CC-BY-SA
https://commons.wikimedia.org/wiki/File:Gold_rings_and_beads_with_granulated_decoration.JPG,

Copper is a good conductor of electricity and is very flexible and ductile. This metal is widely used to conduct electric current in a variety of appliances, from lamps to stereo systems to complex electronic devices (see Figure below).

Copper wire exposed.

Stranded Lamp Wire, CC0

Mercury is the only metal to exist as a liquid at room temperature (see Figure below). This metal was extensively used in thermometers for decades until information about its toxicity became known. Mercury switches were once common, but are no longer used. However, new federally-mandated energy-efficient light bulbs that are now used contain trace amounts of mercury and represent hazardous waste.

Pouring Mercury.

Pouring liquid mercury bionerd by Bionerd, https://commons.wikimedia.org/wiki/File:Pouring_liquid_mercury_bionerd.jpg, CC-BY

When we sort parts in our shop or garage, we often classify them in terms of common properties. One container might hold all the screws (possibly sub-divided by size and type). Another container would be for nails. Maybe there is a set of drawers for plumbing parts.

When you get finished, you could also have a collection of things that don't nicely fit a category. You define them in terms of what they are not. They are not electrical components, or sprinkler heads for the yard, or parts for the car. These parts may have some common properties, but are a variety of items.

Nonmetals

In the chemical world, these “spare parts” would be considered nonmetals, loosely defined as not having the properties of metals. A nonmetal is an element that is generally a poor conductor of heat and electricity. Most properties of nonmetals are the opposite of metals. There is a wider variation in properties among the nonmetals than among the metals. Nonmetals exist in all three states of matter. The majority are gases, such as nitrogen and oxygen. Bromine is a liquid. A few are solids, such as carbon and sulfur. In the solid state, nonmetals are brittle, meaning that they will shatter if struck with a hammer. The solids are not lustrous. Melting points are generally much lower than those of metals. The green elements in the table below are nonmetals.

Nonmetals have a wide variety of uses. Sulfur can be employed in gunpowder, fireworks, and matches to facilitate ignition (see Figure below). This element is also widely used as an insecticide, a fumigant, or a means of eliminating certain types of fungus. An important role for sulfur is the manufacture of rubber for tires and other materials. First discovered in 1839 by Charles Goodyear, the process of vulcanization makes rubber more flexible and elastic as well as being more resistant to changes in temperature. A major use of sulfur is for the preparation of sulfur-containing compounds such as sulfuric acid.

Sulfur.

Sulfur-sample, CC0

Bromine is a versatile element, used mainly in the manufacture of flame-retardant materials, especially important for children's clothing (see Figure below). For treatment of water in swimming pools and hot tubs, bromine is beginning to replace chlorine as a disinfectant because of its higher effectiveness. When incorporated into compounds, bromine atoms play important roles in pharmaceuticals for treatment of pain, cancer, and Alzheimer's disease.

Bromine-ampoule by Jurii, https://commons.wikimedia.org/wiki/File:Bromine-ampoule.jpg, CC-BY

Bromine.

Helium is one of the many nonmetals that is a gas. Other nonmetal gases include hydrogen, fluorine, chlorine, and all the group eighteen noble (or inert) gases. Helium is chemically non-reactive, so it is useful for applications such as balloons (see Figure below) and lasers, where non-flammability is extremely important. Liquid helium exists at an extremely low temperature and can be used to cool superconducting magnets for imaging studies (MRI, magnetic resonance imaging). Leaks in vessels and many types of high-vacuum apparatus can be detected using helium. Inhaling helium changes the speed of sound, producing a higher pitch in your voice. This is definitely an unsafe practice and can lead to physical harm and death.

Goodyear-blimp, CC0

Metalloids

Some elements are "none of the above." They don't fit neatly into the categories of metal or non-metal because of their characteristics. A metalloid is an element that has properties that are intermediate between those of metals and nonmetals. Metalloids can also be called semimetals. On the periodic table, the elements colored yellow, which generally border the stair-step line, are considered to be metalloids. Notice that aluminum borders the line, but it is considered to be a metal since all of its properties are like those of metals.

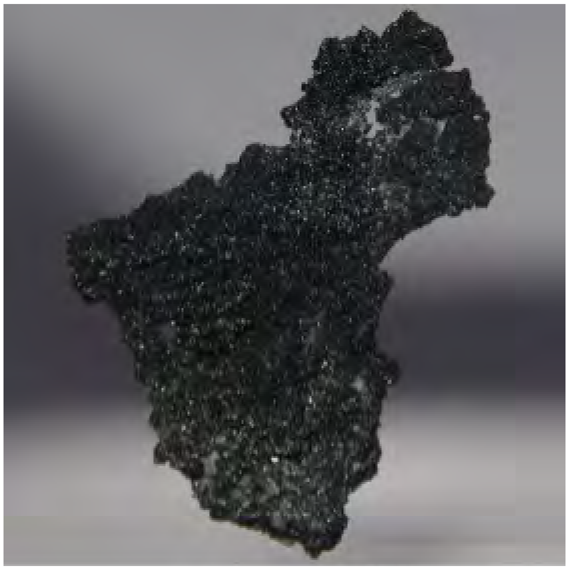
Examples of Metalloids

Silicon Croda, CC0

Silicon is a typical metalloid. It has a luster like metal, but is brittle like a nonmetal. Silicon is used extensively in computer chips and other electronics because its electrical conductivity is in between that of a metal and a nonmetal.

Silicon.

Boron is a versatile element that can be incorporated into a number of compounds (see Figure below). Borosilicate glass is extremely resistant to thermal shock. Extreme changes in the temperature of objects containing borosilicates will not create any damage to the material, unlike other glass compositions, which would crack or shatter. Because of their strength, boron filaments are used as light, high-strength materials for airplanes, golf clubs, and fishing rods. Sodium tetraborate is widely used in fiberglass as insulation and also is employed in many detergents and cleaners.



Boron by Jurii, CC-BY https://commons.wikimedia.org/wiki/File:Boron.jpg,

Native arsenic, CC0

Arsenic has long played a role in murder mysteries, being used to commit the foul deed (see Figure below). This use of the material is not very smart since arsenic can be easily detected on autopsy. We find arsenic in pesticides, herbicides, and insecticides, but the use of arsenic for these applications is decreasing due to the toxicity of the metal. Its effectiveness as an insecticide has led arsenic to be used as a wood preservation.

Antimony massive, CC0

Antimony is a brittle, bluish-white metallic material that is a poor conductor of electricity (see Figure below). Used with lead, antimony increases the hardness and strength of the mixture. This material plays an important role in the fabrication of electronic and semiconductor devices. About half of the antimony used industrially is employed in the production of batteries, bullets, and alloys.

Atomic Radius

The size of atoms is important when trying to explain the behavior of atoms or compounds. One of the ways we can express the size of atoms is with the atomic radius. This data helps us understand why some molecules fit together and why other molecules have parts that get too crowded under certain conditions.

The size of an atom is defined by the edge of its orbital. However, orbital boundaries are fuzzy and in fact are variable under different conditions. In order to standardize the measurement of atomic radii, the distance between the nuclei of two identical atoms bonded together is measured. The atomic radius is defined as one-half the distance between the nuclei of identical atoms that are bonded together.

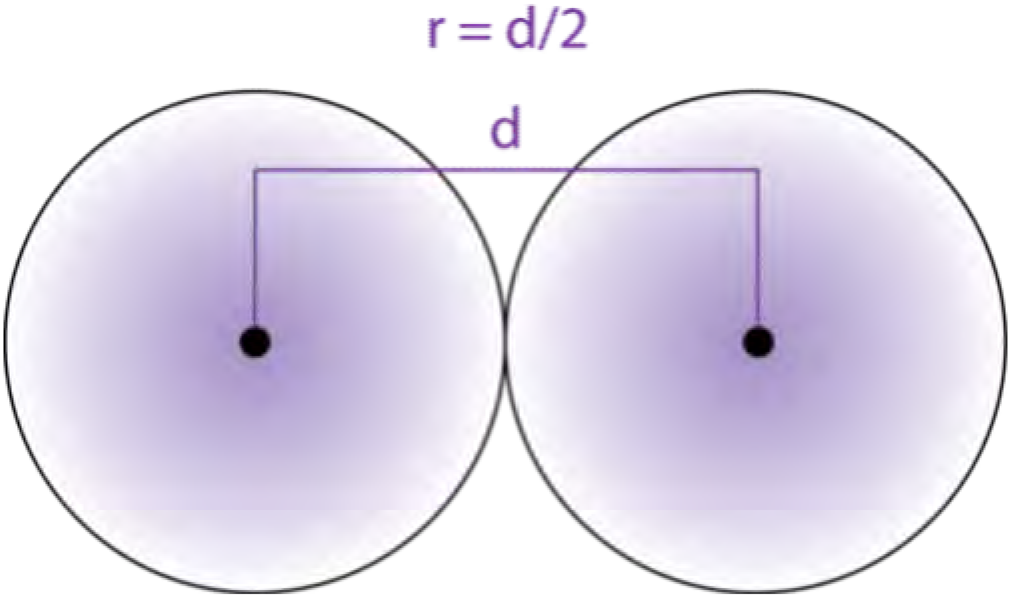


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

The atomic radius (r) of an atom can be defined as one half the distance (d) between two nuclei in a diatomic molecule.

Atomic radii have been measured for elements. The units for atomic radii are picometers, equal to 10^{-12} meters. As an example, the internuclear distance between the two hydrogen atoms in an H_2 molecule is measured to be 74 pm. Therefore, the atomic radius of a hydrogen atom is

742=37 pm

.

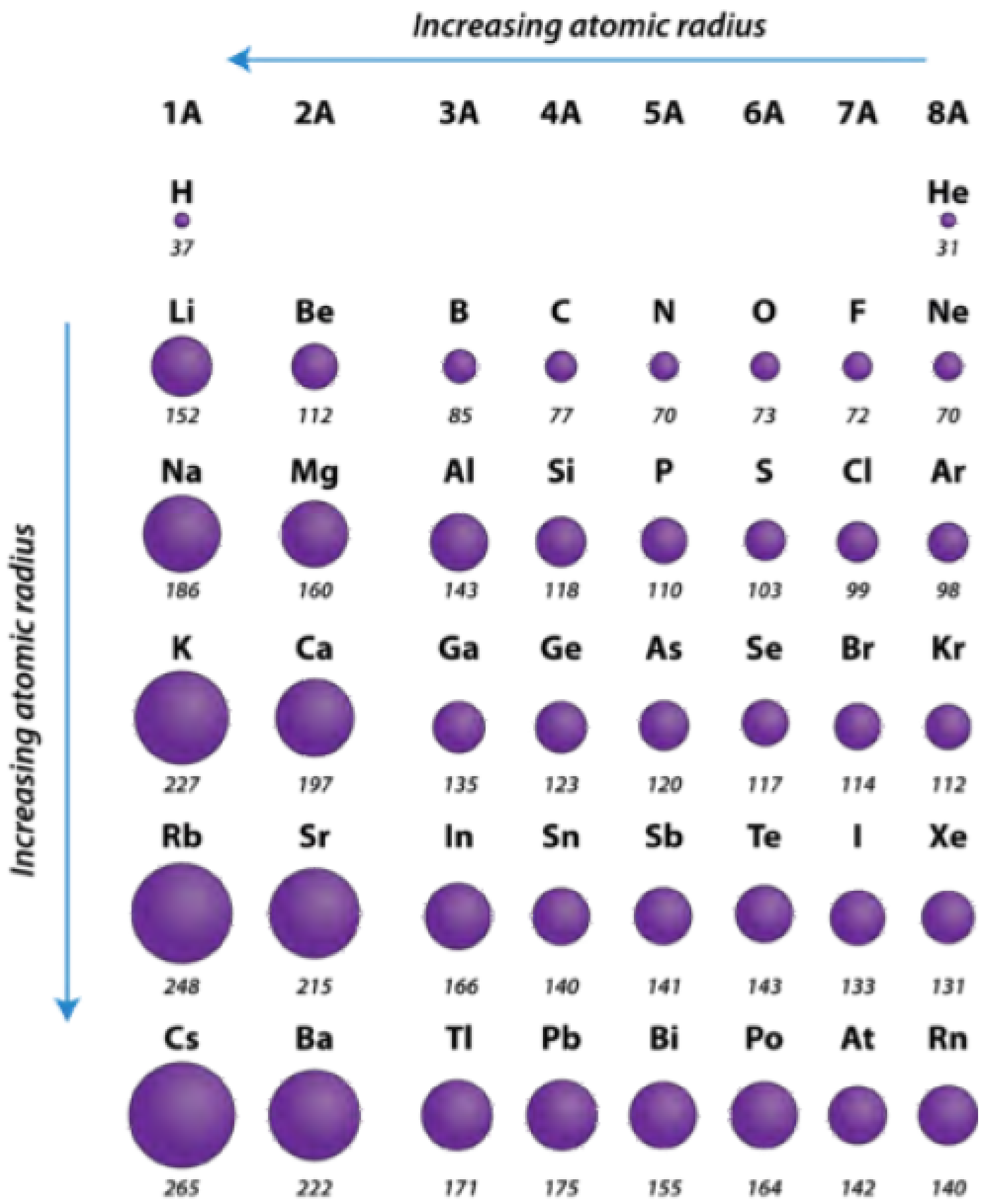


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

Atomic radii of the representative elements measured in picometers.

Periodic Trend

The atomic radius of atoms generally decreases from left to right across a period. There are some small exceptions, such as the oxygen radius being slightly greater than the nitrogen radius. Within a period, protons are added to the nucleus as electrons are being added to the same principal energy level. These electrons are gradually pulled closer to the nucleus because of its increased positive charge. Since the force of attraction between nuclei and electrons increases, the size of the atoms decreases. The effect lessens as one moves further to the right in a period because of electron-electron repulsions that would otherwise cause the atom's size to increase.

Group Trend

The atomic radius of atoms generally increases from top to bottom within a group. As the atomic number increases down a group, there is again an increase in the positive nuclear charge. However, there is also an increase in the number of occupied principle energy levels. Higher principal energy levels consist of orbitals which are larger in size than the orbitals from lower energy levels. The effect of the greater number of principal energy levels outweighs the increase in nuclear charge and so atomic radius increases down a group.

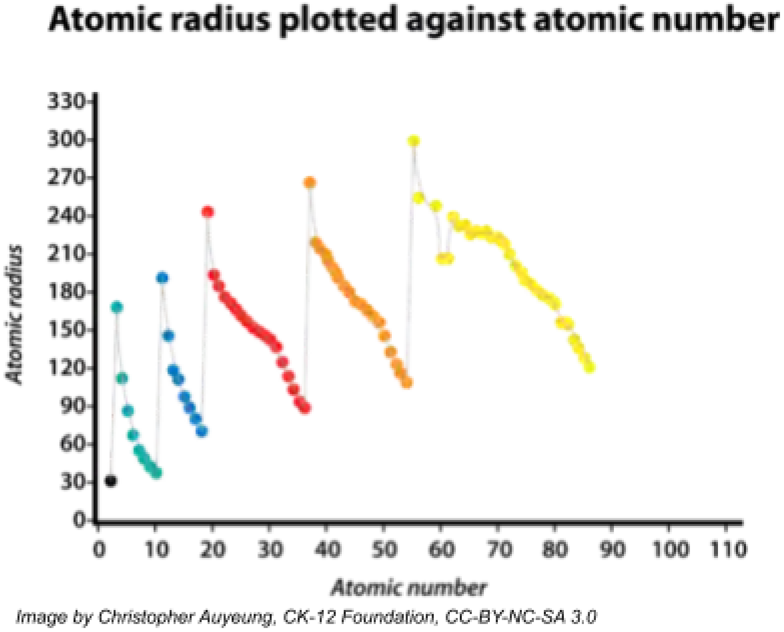


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

A graph of atomic radius plotted versus atomic number. Each successive period is shown in a different color. As the atomic number increases within a period, the atomic radius decreases.

Atoms to Ions

Atoms cannot only gain extra electrons. They can also lose electrons. In either case, they become ions. Ions are atoms that have a positive or negative charge because they have unequal numbers of protons and electrons. If atoms lose electrons, they become positive ions, or cations. If atoms gain electrons, they become negative ions, or anions. Consider the example of fluorine (see Figure below). A fluorine atom has nine protons and nine electrons, so it is electrically neutral. If a fluorine atom gains an electron, it becomes a fluoride ion with an electric charge of -1.

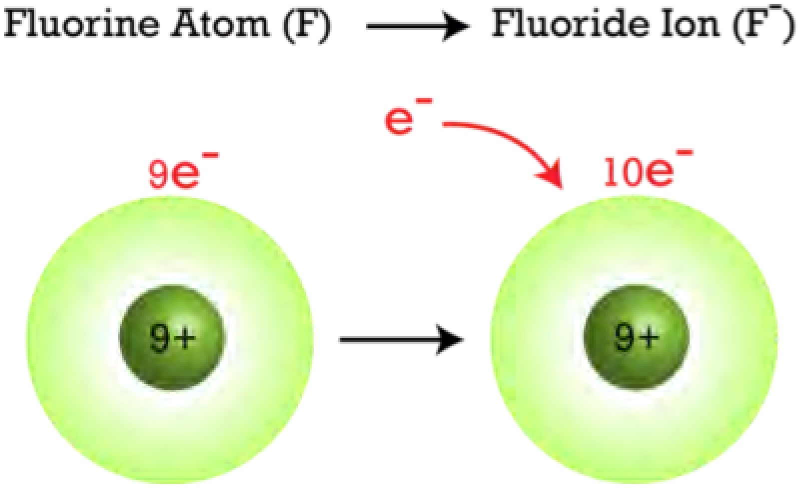


Image by Christopher Auyeung and Zachary Wilson, CK-12 Foundation, CC-BY-NC 3.0

How Ions Form

The process in which an atom becomes an ion is called ionization. It may occur when atoms are exposed to high levels of radiation. The radiation may give their outer electrons enough energy to escape from the attraction of the positive nucleus. However, most ions form when atoms transfer electrons to or from other atoms or molecules. For example, sodium atoms may transfer electrons to chlorine atoms. This forms positive sodium ions (Na^+) and negative chloride ions (Cl^-).

Atoms form ions by losing or gaining electrons because it makes the atom more stable and this state takes less energy to maintain. The most stable state for an atom is to have its outermost energy level filled with the maximum possible number of electrons. In the case of metals such as lithium, with just one electron in the outermost energy level, a more stable state can be achieved by losing that one outer electron. In the case of nonmetals such as fluorine, which has seven electrons in the outermost energy level, a more stable state can be achieved by gaining one electron and filling up the outer energy level.

Properties of Ions

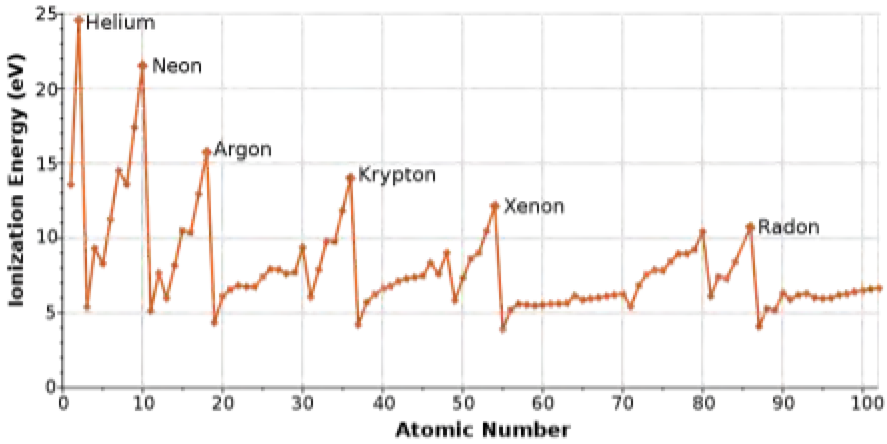
Ions are highly reactive, especially as gases. They usually react with ions of opposite charge to form neutral compounds. For example, positive sodium ions and negative chloride ions react to form the neutral compound sodium chloride, commonly known as table salt. This occurs because oppositely charged ions attract each other. Ions with the same charge, on the other hand, repel each other. Ions are also deflected by a magnetic field, as you saw in the opening image of the northern lights.

Ionization Energy

Ionization energy is the energy required to remove an electron from a specific atom. It is measured in kJ/mol, which is an energy unit, much like calories. The ionization energies associated with some elements are described in Table below. For any given atom, the outermost valence electrons will have lower ionization energies than the inner-shell kernel electrons. As more electrons are added to a nucleus, the outer electrons become shielded from the nucleus by the inner shell electrons. This is called electron shielding.

Element	IE$_1$	IE$_2$	IE$_3$	IE$_4$	IE$_5$	IE$_6$
H	1312					
He	2373	5251				
Li	520	7300	11,815			
Be	899	1757	14,850	21,005		
B	801	2430	3660	25,000	32,820	
C	1086	2350	4620	6220	38,000	47,261
N	1400	2860	4580	7500	9400	53,000
O	1314	3390	5300	7470	11,000	13,000

If we plot the first ionization energies vs. atomic number for the main group elements, we would have the following trend:



Ionization energies, CC0

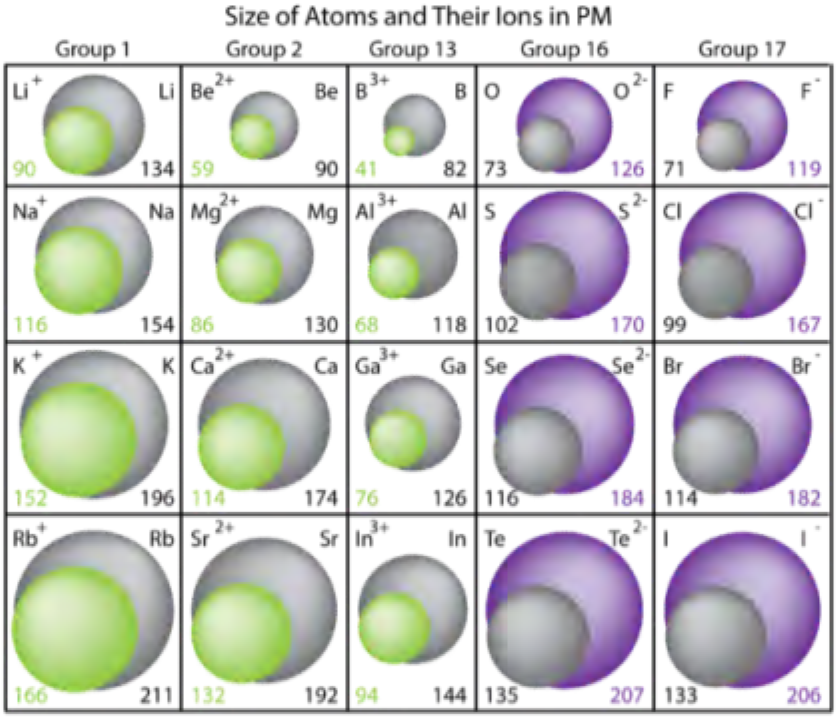
Ionization energy and atomic number.

Moving from left to right across the periodic table, the ionization energy for an atom increases. We can explain this by considering the nuclear charge of the atom. The more protons in the nucleus, the stronger the attraction of the nucleus to electrons. This stronger attraction makes it more difficult to remove electrons.

Within a group, the ionization energy decreases as the size of the atom gets larger. On the graph, we see that the ionization energy increases as we go up the group to smaller atoms. In this situation, the first electron removed is farther from the nucleus as the atomic number (number of protons) increases. Being farther away from the positive attraction makes it easier for that electron to be pulled off.

Ionic Radius

The ionic radius for an atom is measured in a crystal lattice, requiring a solid form for the compound. These radii will differ somewhat depending upon the technique used. Usually X-ray crystallography is employed to determine the radius for an ion.



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Comparison of ion sizes to atom sizes for Groups 1, 2, 13, 16 and 17. The atoms are shown in gray. Groups 1, 2, and 13 are metals and form cations, shown in red. Groups 16 and 17 are nonmetals and form anions, shown in blue.

The removal of electrons always results in a cation that is considerably smaller than the parent atom. When the valence electron(s) are removed, the resulting ion has one fewer occupied principal energy level, so the electron cloud that remains is smaller. Another reason is that the remaining electrons are drawn closer to the nucleus because the protons now outnumber the electrons. One other factor is the number of electrons removed. The potassium atom has one electron removed to for the corresponding ion, while calcium loses two electrons.

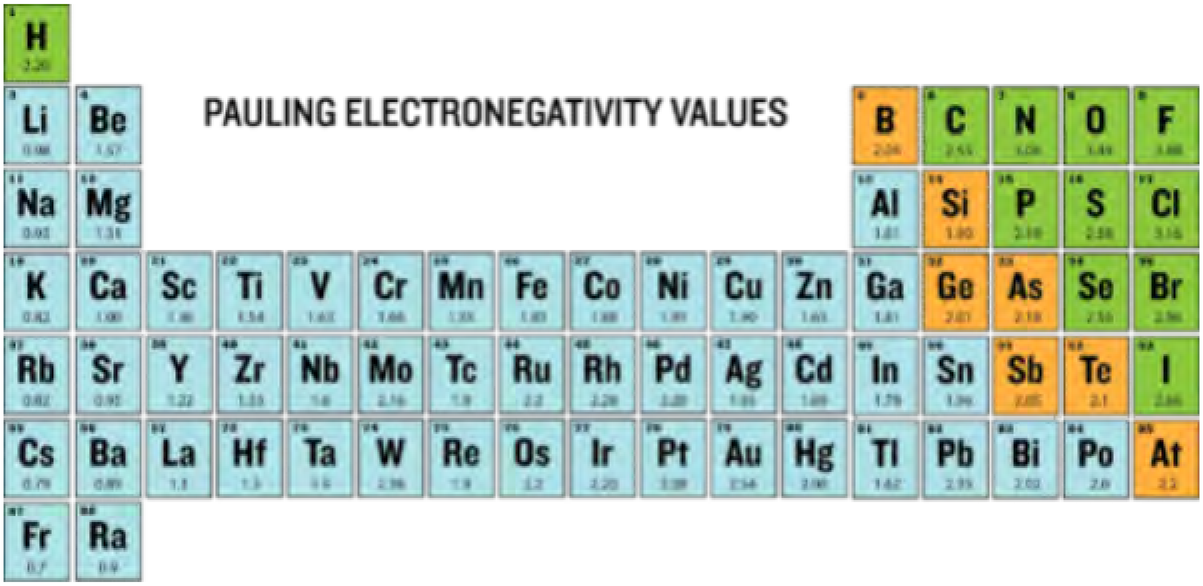
The addition of electrons always results in an anion that is larger than the parent atom.

When the electrons outnumber the protons, the overall attractive force that the protons have for the electrons is decreased. The electron cloud also spreads out because more electrons results in greater electron-electron repulsions. Notice that the group 16 ions are larger than the group 17 ions. The group 16 elements each add two electrons while the group 17 elements add one electron per atom to form the anions.

Electronegativity

Valence electrons of both atoms are always involved when those two atoms come together to form a chemical bond. Chemical bonds are the basis for how elements combine with one another to form compounds. When these chemical bonds form, atoms of some elements have a greater ability to attract the valence electrons involved in the bond than other elements.

Electronegativity is a measure of the ability of an atom to attract electrons when the atom is part of a compound. Electronegativity differs from electron affinity because electron affinity is the actual energy released when an atom gains an electron. Electronegativity is not measured in energy units, but is rather a relative scale. All elements are compared to one another, with the most electronegative element, fluorine, being assigned an electronegativity value of 3.98. Fluorine attracts electrons better than any other element. The table below shows the electronegativity values for the elements.



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The electronegativity scale was developed by Nobel Prize winning American chemist Linus Pauling. The largest electronegativity (3.98) is assigned to fluorine and all other electronegativities measurements are on a relative scale.

Since metals have few valence electrons, they tend to increase their stability by losing electrons to become cations. Consequently, the electronegativities of metals are generally low. Nonmetals have more valence electrons and increase their stability by gaining electrons to become anions. The electronegativities of nonmetals are generally high.

Trends

Electronegativities generally increase from left to right across a period. This is due to an increase in nuclear charge. Alkali metals have the lowest electronegativities, while halogens have the highest. Because most noble gases do not form compounds, they do not have electronegativities. Note that there is little variation among the transition metals. Electronegativities generally decrease from top to bottom within a group due to the larger atomic size.

Of the main group elements, fluorine has the highest electronegativity (EN = 4.0) and cesium the lowest (EN = 0.79). This indicates that fluorine has a high tendency to gain electrons from other elements with lower electronegativities. We can use these values to predict what happens when certain elements combine. The following video shows this.

When the difference between electronegativities is greater than ~1.7, then a complete exchange of electrons occurs. Typically this exchange is between a metal and a nonmetal. For instance, sodium and chlorine will typically combine to form a new compound and each ion becomes isoelectronic with its nearest noble gas. When we compare the EN values, we see that the electronegativity for Na is 0.93 and the value for Cl is 3.2. The absolute difference between ENs is |0.93 - 3.2| = 2.27. This value is greater than 1.7, and therefore indicates a complete electron exchange occurs.

Putting It Together

Image from US Department of Energy, Public domain

Let us revisit the phenomenon:

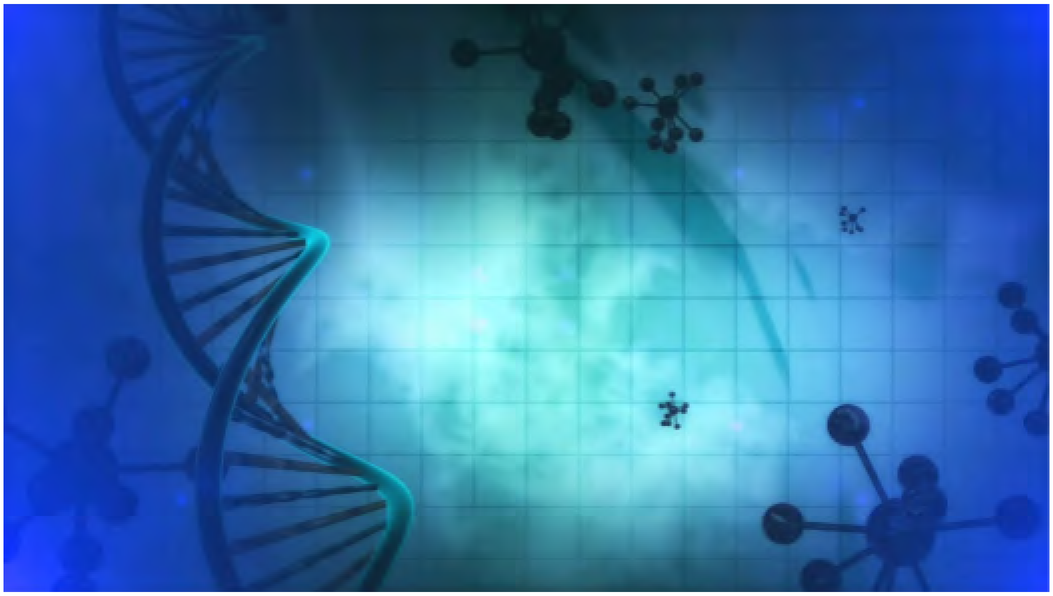
Remember the Alkali metals from the beginning of the chapter? You learned that alkali metals react quickly with air and water.

1. Do elements in the same group have the same properties? Why or why not?
2. Do elements in the same period have the same properties? Why or why not?

CHAPTER 2

Strand 2: Structure and Properties of Molecules

Chapter Outline



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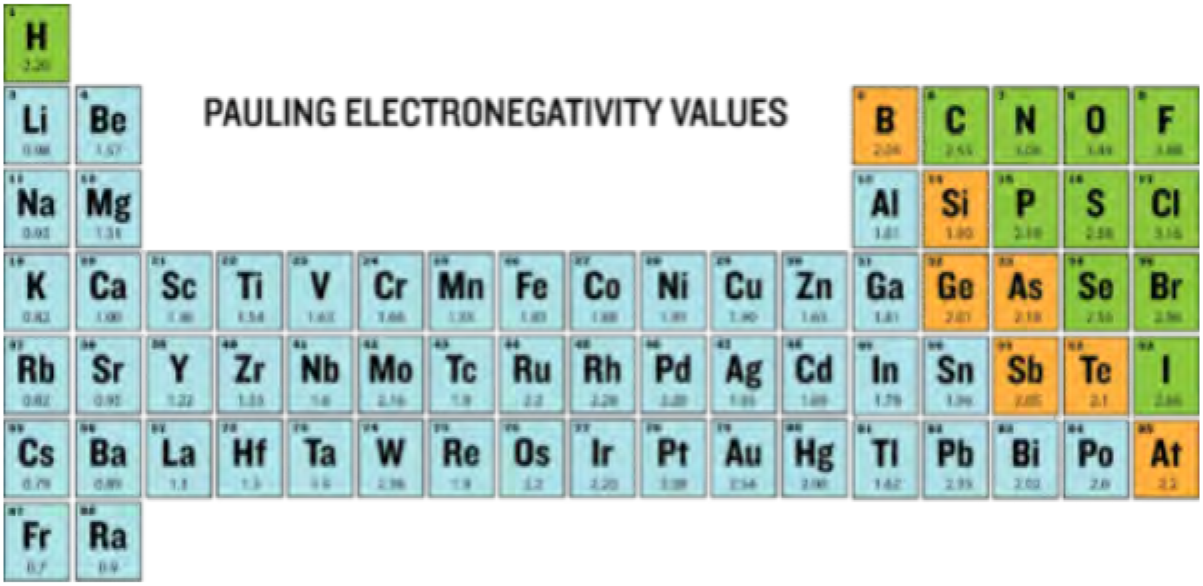
Electrical attractions and repulsions between charged particles (atomic nuclei and electrons) in matter explain the structure of atoms and the forces between atoms that cause them to form molecules via chemical bonds. Molecules can range in size from two atoms to thousands of atoms. The same forces cause atoms to combine to form extended structures, such as crystals or metals. The varied properties of the materials, both natural and manufactured, can be understood in terms of the atomic and molecular particles present and the forces within and between them. Materials are engineered to fulfill a desired function or role with desired properties.

2.1 Bonding (Chem.2.1)

Explore this Phenomenon



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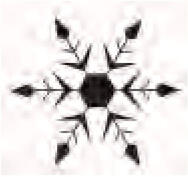
Look at this periodic table showing electronegativity values below the atomic symbol.

1. Which of the main group of elements is missing?
2. What would you expect to happen if you combine calcium and phosphorus? Would you expect it to be different if you combine carbon and phosphorus?
3. What patterns can you find? How does it change going across? How does it change going down the table?

Standard Chem.2.1

Analyze data to predict the type of bonding most likely to occur between two elements using the patterns of reactivity on the periodic table. Emphasize the types and strengths of attractions between charged particles in ionic, covalent, and metallic bonds. Examples could include the attraction between electrons on one atom and the nucleus of another atom in a covalent bond or between ions in an ionic compound. (PS1.A, PS2.B)



In this section, look for patterns of reactivity to explain why certain elements form certain types of bonds. How can you use the patterns you have already learned about the Periodic Table to predict why elements will form compounds and which types of bonds are likely to be formed?

There is an amazing diversity of matter in the universe, but there are only about 100 elements. How can this relatively small number of pure substances make up all kinds of matter? Elements can combine in many different ways. When they do, they form new substances called compounds.

Chemical Bonding

Elements form compounds when they combine chemically. Their atoms join together to form molecules, crystals, or other structures. The atoms are held together by chemical bonds (a force of attraction between atoms or ions). Chemical bonds occur when atoms share or transfer valence electrons (the electrons in the outer energy level of an atom).

Water (H_2O) is an example of a molecule. Water molecules always consist of two atoms of hydrogen and one atom of oxygen. Like water, all other chemical compounds consist of a fixed ratio of elements. It doesn’t matter how much or how little of a molecule/compound there is, this ratio remains constant.

It is important to know that when atoms combine to form compounds, their chemical properties – (an atom’s potential to change through a chemical reaction) and physical properties – (observable, measurable properties) change.

For example, table salt, called sodium chloride, is formed by bonding a sodium atom (Na) to a chlorine atom (Cl). Elemental sodium is a soft metal that reacts with water to produce a flammable gas. Elemental chlorine is a gas at room temperature and is poisonous. These two nasty chemicals join together to form table salt (NaCl); a substance we eat most every day. Sodium (Na) and chlorine (Cl) do not have the same properties as sodium chloride (NaCl). Elements do not have the same chemical and physical properties as when they join to form compounds.

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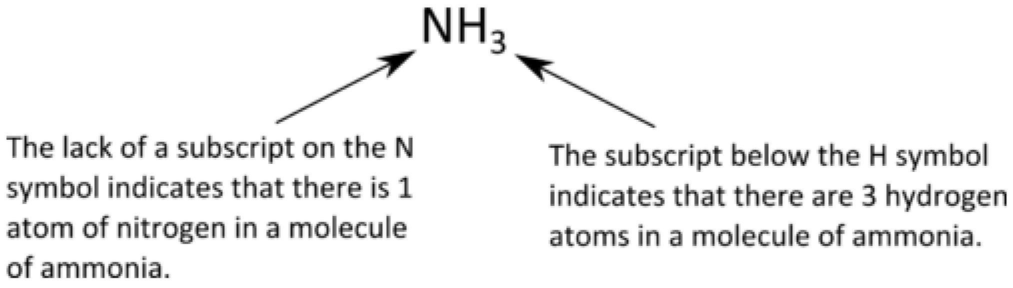
Chemical Formulas

Elements are represented by chemical symbols. Examples are H for hydrogen and O for oxygen. Compounds are represented by chemical formulas – (indicates the types and number of atoms in a chemical compound). You've already seen the chemical formula for water; it's H_2O. The subscript 2 after the H shows that there are two atoms of hydrogen in a molecule of water. The O for oxygen has no subscript. When there is just one atom of an element in a molecule, no subscript is used. The table below shows some other examples of compounds and their chemical formulas.

Name of Compound	**Numbers of Atoms**	**Chemical Formula**
Hydrogen chloride	H = 1 Cl = 1	HCl
Methane	C = 1 H = 4	CH_4
Hydrogen peroxide	H = 2 O = 2	H_2O_2
Carbon dioxide	C = 1 O = 2	CO_2



The lack of a subscript on the N symbol indicates that there is 1 atom of nitrogen in a molecule of ammonia.

The subscript below the H symbol indicates that there are 3 hydrogen atoms in a molecule of ammonia.

Did you ever play the card game called Go Fish? Players try to form groups of cards of the same value, such as four sevens, with the cards they are dealt or by getting cards from other players or the deck. This give and take of cards is a simple analogy for the way atoms give and take valence electrons in chemical reactions.

What Are Valence Electrons?

To understand chemical bonding, we first must understand valence electrons – (the electrons in the outer energy level of an atom). Valence electrons can participate in interactions with other atoms. Valence electrons are generally the electrons that are farthest from the nucleus. As a result, they may be attracted as much or more by the nucleus of another atom than they are by their own nucleus.

Electron Dot Diagrams

Because valence electrons are so important, atoms are often represented by simple diagrams that show only their valence electrons. These are called electron dot diagrams, and two are shown below.

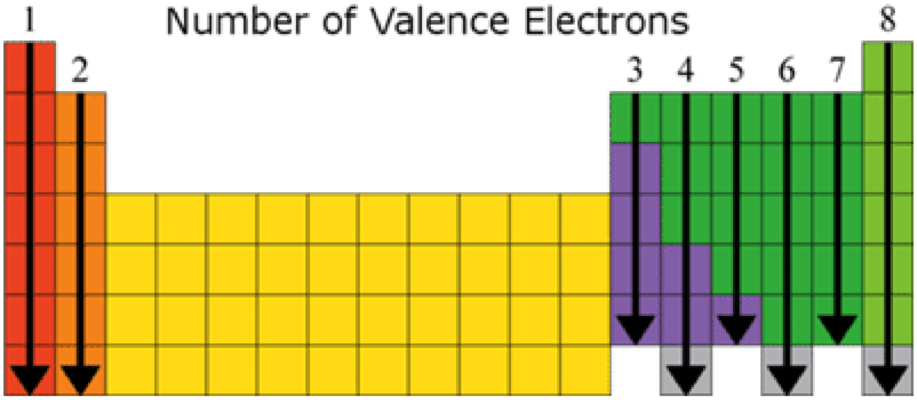
In this type of diagram, an element's chemical symbol is surrounded by dots that represent the valence electrons. Typically, the dots are drawn as if there is a square surrounding the element symbol with up to two dots per side. Eight electrons complete an element’s valence shell, so we draw up to eight dots per atom.

Valence Electrons and the Periodic Table

The number of valence electrons in an atom is reflected by its position in the periodic table of the elements (see the periodic table below). Across each row, or period, of the periodic table, the number of valence electrons in groups 1–2 and 13–18 increases by one from one element to the next. Within each column, or group, of the table, all the elements have the same number of valence electrons. This explains why all the elements in the same group have very similar chemical properties.

For elements in groups 1–2 and 13–18, the number of valence electrons is easy to tell directly from the periodic table. This is illustrated in the simplified periodic table in the figure below. It shows just the numbers of valence electrons in each of these groups.

For elements in groups 3–12, determining the number of valence electrons is more complicated and goes beyond the scope of this course.



Valence Electrons and Reactivity

The number of valence electrons of an atom will determine its reactivity with other atoms. Atoms are more stable when they have full outer shells. In other words, stable atoms have full octet (8 valence electrons). The noble gas elements are the most stable, and therefore the least reactive of all the elements on the periodic table, because they already have eight valence electrons. Their valence shells are full. Atoms will bond or react with other atoms to become stable with full outer shells, or full octets. Some atoms will be more reactive than other atoms depending on their valence electrons. For example, fluorine is highly reactive because it has seven valence electrons and only needs one more electron to for a full octet, which makes the atom more stable. While most atoms are most stable with eight valence electrons, hydrogen is one exception because it only needs two valence electrons to fill its valence shell.

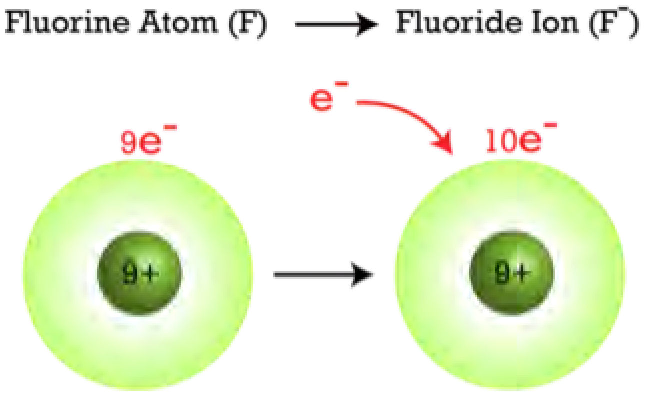
Atoms Are Neutral

An atom always has the same number of electrons as protons. Electrons have an electric charge of -1 and protons have an electric charge of +1. Therefore, the charges of an atom's electrons and protons "cancel out". This explains why atoms are neutral in electric charge.

What would happen to an atom's charge if it were to gain extra electrons? It would have more electrons than protons. This would give it a negative charge, so it would no longer be neutral.

Atoms to Ions

Atoms cannot only gain extra electrons. They can also lose electrons. In either case, they become ions – (atoms that have a charge because they have gained or lost electrons). Ions are atoms that have a positive or negative charge because they have unequal numbers of protons and electrons. Atoms will gain or lose electrons in this process, but the amount of protons will stay the same. If atoms lose electrons, they become cations – (positive ions). If atoms gain electrons, they become anions – (negative ions). Consider the example of fluorine (see Figure below). A fluorine atom has nine protons and nine electrons and is electrically neutral. If a fluorine atom gains an electron, it becomes a fluoride ion with an electric charge of -1.



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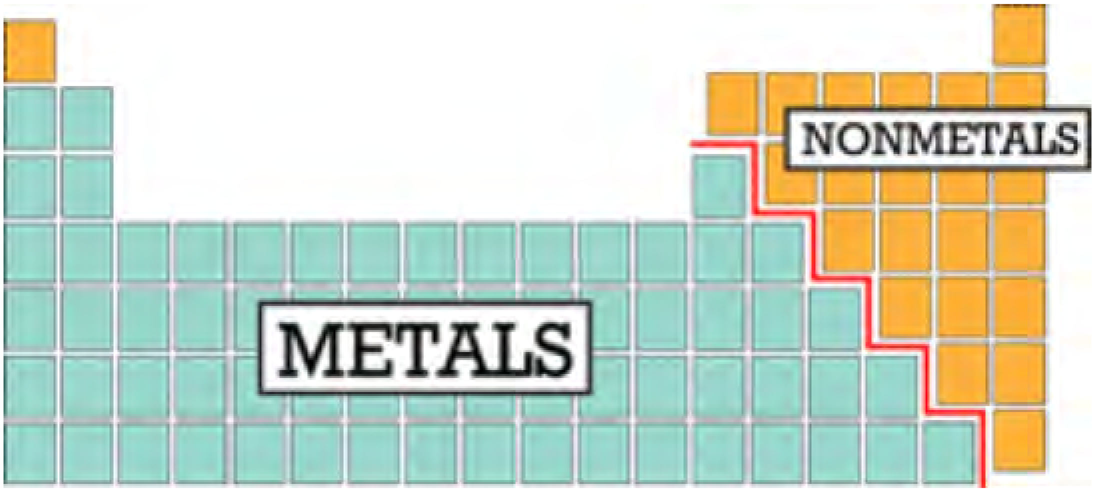
Metals and Nonmetals



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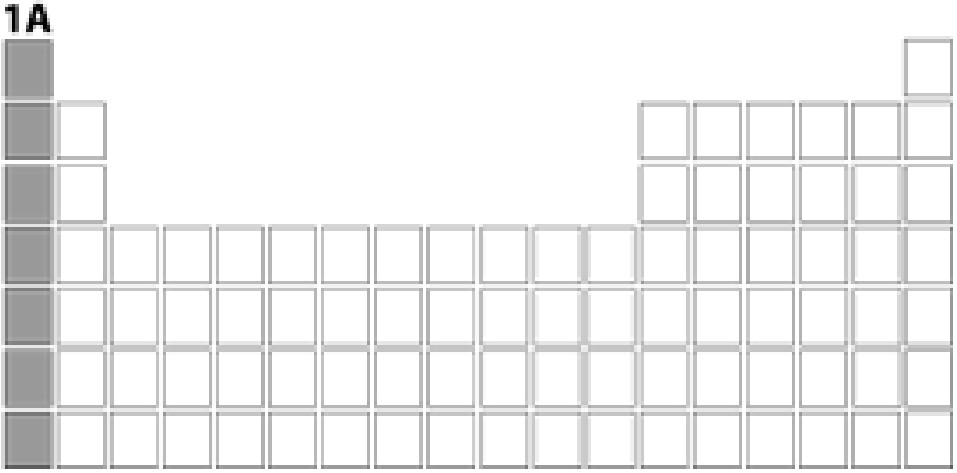
As mentioned above, atoms lose or gain electrons to become stable.

Which atoms gain electrons and which atoms lose electrons? Metals, the atoms found on the left side of the table, tend to lose electrons and become cations; while nonmetals tend to gain electrons and become anions. Noble gases do not form ions.

Atoms form ions by losing or gaining electrons because it makes them more stable. The most stable state for an atom is to have its outermost energy level filled. In the case of metals such as lithium, with just one valence electron in the outermost energy level, a more stable state can be achieved by losing that one outer electron. In the case of nonmetals such as fluorine, which has seven valence electrons in the outermost energy level, a more stable state can be achieved by gaining one electron and filling up the outer energy level.

Some Common Ions

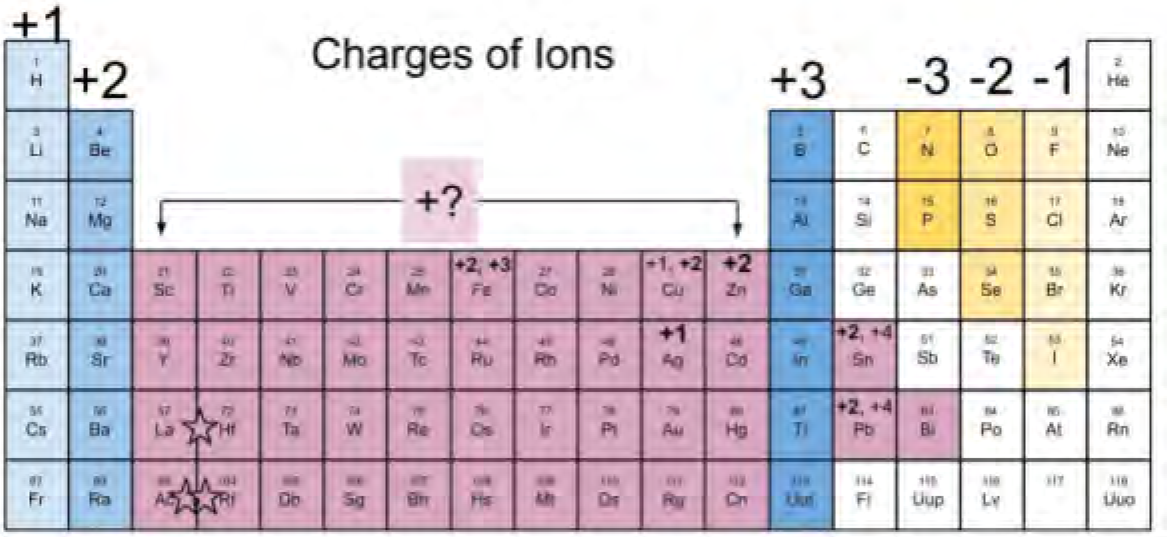
All the metals in family 1A (shown in the figure below) have one valence electron. The entire family forms +1 ions: Li^+, Na^+, K^+, Rb^+, Cs^+, and Fr^+. Note that although hydrogen (H) is in this same column, it is not considered to be a metal. There are times when hydrogen acts like a metal and forms +1 ions, but most of the time it bonds with other atoms as a nonmetal. In other words, hydrogen doesn't easily fit into any chemical family.



The metals in family 2A all have two valence electrons. This entire family will form +2: Be^{+2}, Mg^{+2}, Ca^{+2}, Sr^{+2}, Ba^{+2}, Ra^{+2}.

The elements in Family 3A each have three valence electrons. When these atoms form ions, they will almost always form +3 ions: Al^{+3}, Ga^{+3}, In^{+3}, Ti^{+3}. Notice that boron is omitted from this list. This is because boron falls on the nonmetal side of the metal/nonmetal dividing line. Boron generally doesn't lose all of its valence electrons during chemical reactions.

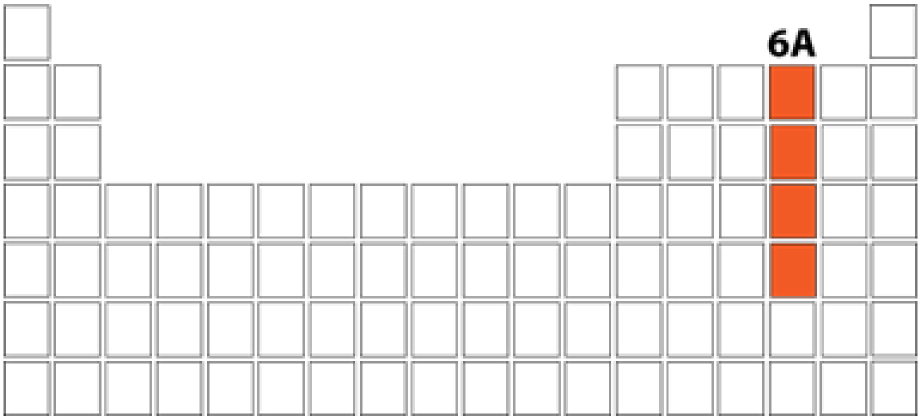
Family 4A is almost evenly divided into metals and nonmetals. The larger atoms in the family (germanium, tin, and lead) are metals. Since these atoms have 4 valence electrons, they are expected to form ions with charges of +4. All three of the atoms do form such ions (Ge^{+4}, $Sn^{+4}$and Pb^{+4}), but tin and lead also have the ability to also form +2 ions.



Tracy Poulsen, CC-BY

Like family 4A, the elements of family 5A are also divided into metals and nonmetals. The smaller atoms in this family behave as nonmetals and form -3 ions, and the larger atoms behave as metals that form +5 ions. For the nonmetals, they each have 5 valence electrons so they will need to gain 3 more hence, the -3 charge.

Most of the elements in family 6A (shown in figure below) are nonmetals that have 6 valence electrons. They form -2 ions. If you consider that each has six valence electrons, they will need to gain two more to become stable: O^{-2}, S^{-2}, Se^{-2} and Te^{-2}.



Family 7A are all nonmetals. When these atoms form ions, they form -1 ions: F^{-}, Cl^{-}, Br^{-} and I^{-}. They each have seven valence electrons therefore; they need to gain one more to be stable.

Family 8A, of course, is made up of the noble gases, which have no tendency to either gain or lose electrons.

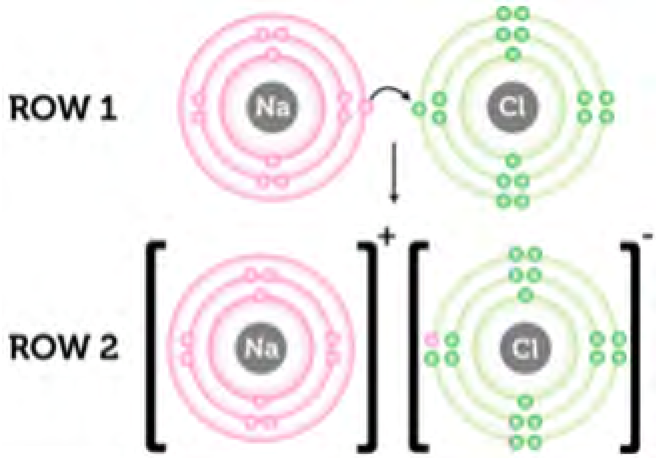
Types of Chemical Bonds - Depending on where elements lie on the periodic table, it will form one of three types of bonds - ionic, covalent, or metallic.

- An ionic bond is the force of attraction that holds together oppositely charged ions. Ionic bonds form crystals instead of molecules.
- A metallic bond is the force of attraction between a positive metal ion and the valence electrons that surround it—both its own valence electrons and those of other ions of the same metal. The ions and electrons form a lattice-like structure. Only metals form metallic bonds.
- A covalent bond is the force of attraction that holds together two nonmetal atoms that share a pair of electrons. One electron is provided by each atom, and the pair of electrons is attracted to the positive nuclei of both atoms.

Formation of Ionic Bonds

All compounds form when atoms of different elements share or transfer electrons. In the strongest type of bonds called ionic compounds, the electrons actually move from one atom to another. When atoms transfer electrons in this way, they become charged particles called ions. The ions are held together by ionic bonds.

An ionic bond (the force of attraction that holds together positive and negative ions) forms when atoms of a metallic element give up electrons to atoms of a nonmetallic element. The figure shows how this happens.



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An ionic bond forms when the metal sodium gives up an electron to the nonmetal chlorine.

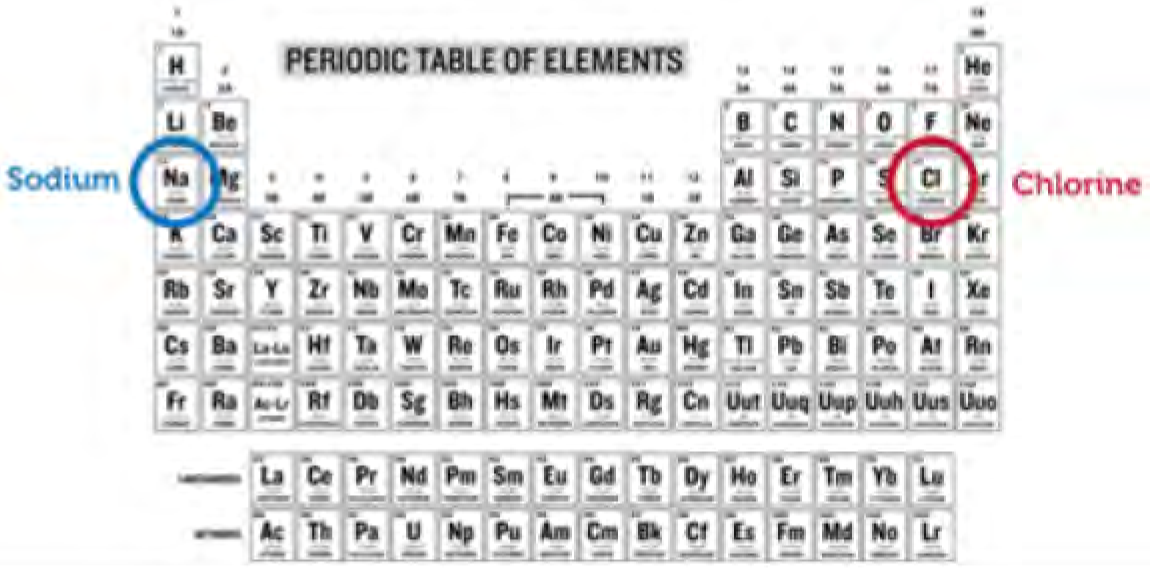
By losing an electron, the sodium atom becomes a sodium ion. It now has one less electron than protons, giving it a charge of +1. Positive ions such as sodium are given the same name as the element. The chemical symbol has a plus sign to distinguish the ion from an atom of the element. The symbol for a sodium ion is Na+.

By gaining an electron, the chlorine atom becomes a chloride ion. It now has one more electron than protons, giving it a charge of -1. Negative ions are named by adding the suffix -ide to the first part of the element name. The symbol for chloride is Cl-.

Sodium and chloride ions have opposite charges. Opposites attract, so sodium and chloride ions attract each other. They cling together in a strong ionic bond. You can see this in row 2 of Figure above. Brackets separate the ions in the diagram to show that the ions in the compound do not share electrons.

Why Ionic Bonds Form

Ionic bonds form only between metals and nonmetals. Metals become more stable by giving up electrons, and nonmetals become more stable by gaining electrons. Find sodium (Na) on the periodic table - Sodium is an alkali metal in group 1. Like other group 1 elements, it has just one valence electron. If sodium loses that one electron, it will have a full outer energy level. Now find chlorine (Cl) on the periodic table - Chlorine is a halogen in group 17. It has seven valence electrons. If chlorine gains one electron, it will have a full outer energy level. After sodium gives up its valence electron to chlorine, both atoms have a more stable arrangement of electrons.



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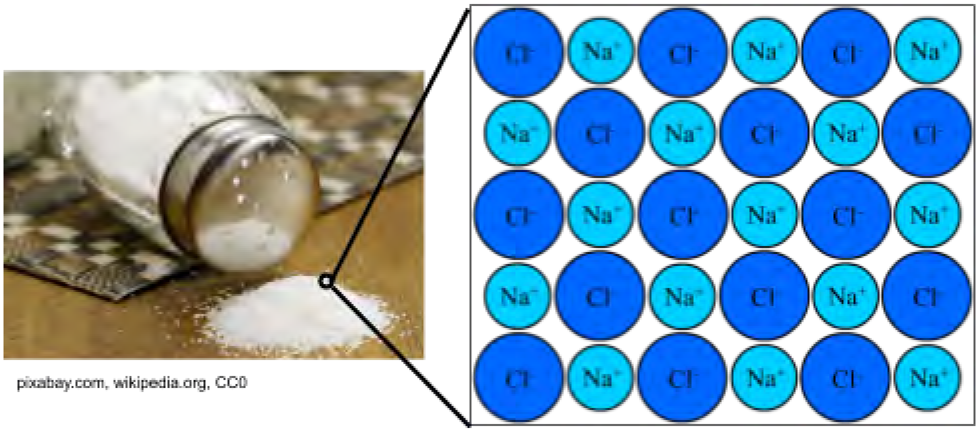
Properties of Ionic Compounds



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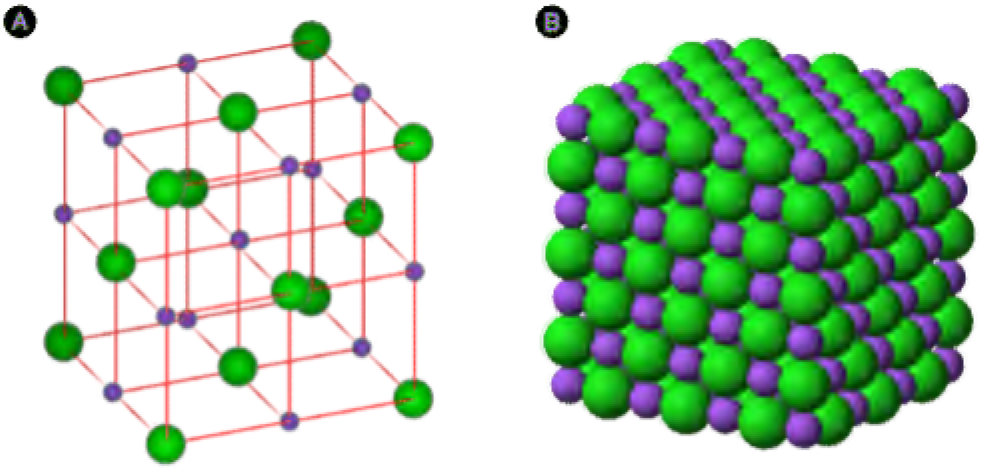

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http://commons.wikimedia.org/wiki/File:Sodium-chloride-3D-ionic.png (Ben Mills, wikimedia)
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Two models of a sodium chloride crystal are shown. The purple spheres represent the Na^+ ions, while the green spheres represent the Cl^- ions. (A) In an expanded view, the distances between ions are exaggerated, more easily showing the coordination numbers of each ion. (B) In a space filling model, the electron clouds of the ions are in contact with each other.

Ionic compounds contain ions of metals and nonmetals held together by ionic bonds. Ionic compounds do not form molecules. Instead, many positive and negative ions bond together to form a structure called a crystal. You can see an example of a crystal in the figure. It shows the ionic compound sodium chloride. Positive sodium ions (Na^+) alternate with negative chloride ions (Cl^-). The oppositely charged ions are strongly attracted to each other.

Writing Basic Ionic Formulas

In writing formulas for binary ionic compounds (binary refers to two elements, not two single atoms), the cation is always written first. Chemists use subscripts following the symbol of each element to indicate the number of that element present in the formula. For example, the formula Na_2O indicates that the compound contains two atoms of sodium for every one atom of oxygen. When the subscript for an element is 1, the subscript is omitted. The number of atoms of an element with no indicated subscript is always read as 1. When an ionic compound forms, the number of electrons given off by the cations must be exactly the same as the number of electrons taken on by the anions. Therefore, if calcium, which gives off two electrons, is to be combined with fluorine, which takes on one electron, then one calcium atom must combine with two fluorine atoms. The formula would be CaF_2.

Suppose we wish to write the formula for the compound that forms between aluminum and chlorine. To write the formula, we must first determine the charges of the ions that would be formed.

$\overset{3+}{\mathrm{Al}} \qquad\qquad \overset{1-}{\mathrm{Cl}}$

Then, we determine the simplest whole numbers with which to multiply these charges so they will balance (add to zero). In this case, we would multiply the 3+ by 1 and the 1- by 3.

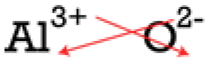
You should note that we could multiply the 3+ by 2 and the 1- by 6 to get 6+ and 6- respectively. These values will also balance, but this is not acceptable because empirical formulas, by definition, must have the lowest whole number multipliers. Once we have the lowest whole number multipliers, those multipliers become the subscripts for the symbols. The formula for this compound would be $AlCl_3$.

Here's the process for writing the formula for the compound formed between aluminum and sulfur.
$Al^{3+}S^{2-}$
Therefore, the formula for this compound would be Al_2S_3.

Another method used to write formulas is called the crisscross method. It is a quick method, but it often produces errors if the user doesn't pay attention to the results. The example below demonstrates the crisscross method for writing the formula of a compound formed from aluminum and oxygen. In the crisscross method, the oxidation numbers are placed over the symbols for the elements just as before.

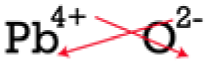
$\overset{3+}{\mathrm{Al}} \qquad\qquad \overset{2-}{\mathrm{O}}$

In this method, the oxidation numbers are then crisscrossed and used as the subscripts for the other atom (ignoring sign).



This produces the correct formula Al_2O_3 for the compound. Here's an example of a crisscross error:

$Pb^{4+} \quad O^{2-}$



Pb_2O_4

PbO_2

If you used the original method of finding the lowest multipliers to balance the charges, you would get the correct formula PbO_2, but the crisscross method produces the incorrect formula Pb_2O_4. If you use the crisscross method to generate an ionic formula, it is essential that you check to make sure that the subscripts correspond to the lowest whole number ratio of the atoms involved.

Polyatomic Ions

Polyatomic ions (charged particles made up of more than one atom) can also be present in ionic compounds. They are a group of bonded atoms with a charge that act like a single ion. Here is a short list of some common polyatomic ions:

Ammonium ion, NH_4^+
Acetate ion, $C_2H_3O_2^-$
Carbonate ion, CO_2^-
Chromate ion, CrO_4^{2-}
Dichromate ion, $Cr_2O_7^{2-}$
Hydroxide ion, OH^-
Nitrate ion, NO_3^-
Phosphate ion, PO_4^{3-}
Sulfate ion, SO_4^{2-}
Sulfite ion, SO_3^{2-}

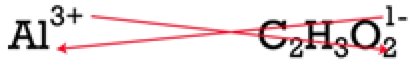
Suppose we are asked to write the formula for the compound that would form between calcium and the nitrate ion. We begin by putting the charges above the symbols just as before.

The multipliers needed to balance these ions are 1 for calcium and 2 for nitrate. We wish to write a formula that tells our readers that there are two nitrate ions in the formula for every calcium ion. When we put the subscript 2 beside the nitrate ion in the same fashion as before, we get something strange – $CaNO_{32}$. With this formula, we are indicating 32 oxygen atoms, which is wrong. The solution to this problem is to put parentheses around the nitrate ion before the subscript is added. Therefore, the correct formula is $Ca\ (NO_3)_2$.

Similarly, calcium phosphate would be $Ca_3\ (PO_4)_2$. If a polyatomic ion does not need a subscript other than an omitted 1, then the parentheses are not needed. Although including these unnecessary parentheses does not change the meaning of the formula, it may cause the reader to wonder whether a subscript was left off by mistake. Try to avoid using parentheses when they are not needed.

Example 1

Write the formula for the compound that will form from aluminum and acetate.



The charge on an aluminum ion is +3, and the charge on an acetate ion is -1. Therefore, three acetate ions are required to combine with one aluminum ion. This is also apparent by the crisscross method. However, we cannot place a subscript of 3 beside the oxygen subscript of 2 without inserting parentheses first. Therefore, the formula will be $Al(C_2H_3O_2)_3$.

Example 2

Write the formula for the compound that will form from ammonium and phosphate.

The charge on an ammonium ion is +1 and the charge on a phosphate ion is -3. Therefore, three ammonium ions are required to combine with one phosphate ion. The crisscross procedure will place a subscript of 3 next to the subscript 4. This can only be carried out if the ammonium ion is first placed in parentheses. Therefore, the proper formula is $(NH_4)_3PO_4$.

Variable Charge Metals

In general, main group metal ions have only one common charge, whereas most of the transition metals have more than one. However, there are plenty of exceptions to this guideline. There are some metals with variable charges where they may form multiple different compounds with the same nonmetal. Iron, for example, may react with oxygen to form either FeO or Fe_2O_3. These are very different compounds with different properties.

The Metallic Bond

Pure metals are crystalline solids, but unlike ionic compounds, every point in the crystal lattice is occupied by an identical atom. The electrons in the outer energy levels of a metal are mobile and capable of drifting from one metal atom to another. This means that the metal is more properly viewed as an array of positive ions surrounded by a sea of mobile valence electrons. A metallic bond is the attraction of the stationary metal cations to the surrounding mobile electrons.

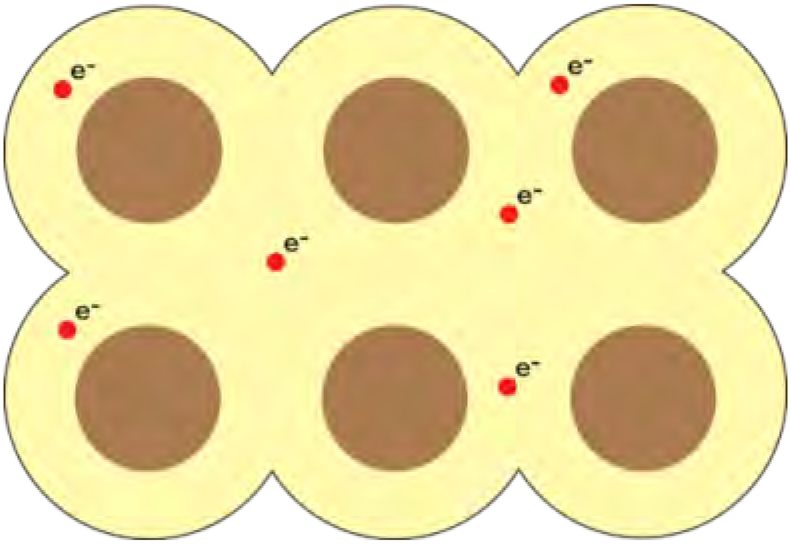


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

In a metal, the stationary metal cations are surrounded by a sea of mobile valence electrons that are not associated with any one cation.

Properties of Metals

The metallic bonding model explains the physical properties of metals. Metals conduct electricity and heat very well because of their free-flowing electrons. As electrons enter one end of a piece of metal, an equal number of electrons flow outward from the other end. Recall that ionic compounds are very brittle. Application of a force results in like-charged ions in the crystal coming too close to one another, causing the crystal to shatter. When a force is applied to a metal, the free-flowing electrons can slip in between the stationary cations and prevent them from coming in contact. As a result, metals are very malleable and ductile. They can be hammered into shapes, rolled into thin sheets, or pulled into thin wires.

Covalent Bonds

In a tennis match, two players keep hitting the ball back and forth. The ball bounces from one player to the other, over and over again. The ball keeps the players moving together on the court. What if the two players represented the nuclei of two atoms and the ball represented valence electrons? What would the back and forth movement of the ball represent? The answer is a covalent bond.

Sharing Electrons

A covalent bond is the force of attraction that holds together two atoms that share a pair of valence electrons. The shared electrons are attracted to the nuclei of both atoms. This forms a molecule consisting of two or more atoms. Covalent bonds form only between atoms of nonmetals.

To understand why chemical bonds form, consider the common compound known as water, or H_2O. It consists of two hydrogen (H) atoms and one oxygen (O) atom. As you can see on the left side of the Figure below, each hydrogen atom has just one electron, which is also its sole valence electron. The oxygen atom has six valence electrons. These are the electrons in the outer energy level of the oxygen atom.

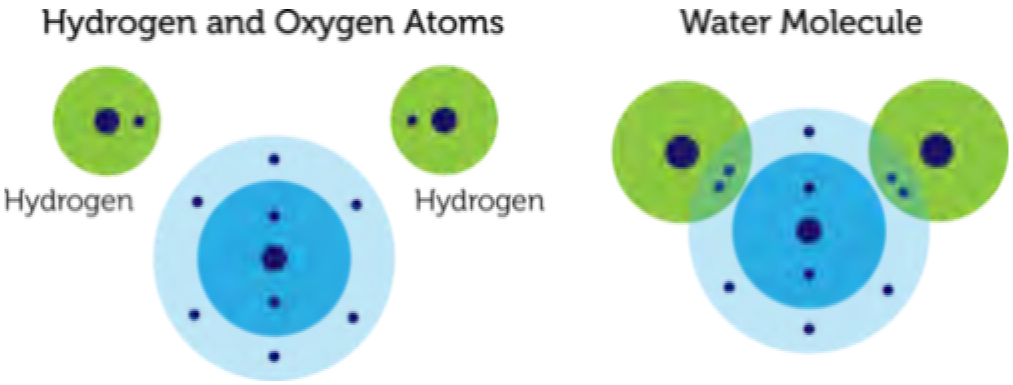


Image by Christopher Auyeung and Zachary Wilson, CK-12 Foundation, CC-BY-NC-3.0

In the water molecule on the right in the Figure above, each hydrogen atom shares a pair of electrons with the oxygen atom. By sharing electrons, each atom has electrons available to fill its sole or outer energy level. The hydrogen atoms each have a pair of shared electrons, so their first and only energy level is full. The oxygen atom has a total of eight valence electrons, so its outer energy level is full. A full outer energy level is the most stable possible arrangement of electrons. It explains why elements form chemical bonds with each other. When atoms of different elements form covalent bonds, a new substance, called a covalent compound, results. A molecule is the smallest particle of a covalent compound that still has the properties of the compound.

Diatomic Elements

The diagram in the Figure below shows an example of covalent bonds between two atoms of the same element, in this case two atoms of oxygen. The diagram represents an oxygen molecule, so it’s not a new compound. Oxygen normally occurs in diatomic (“two-atom”) molecules. Several other elements also occur as diatomic molecules: hydrogen, nitrogen, and all but one of the halogens (fluorine, chlorine, bromine, and iodine).

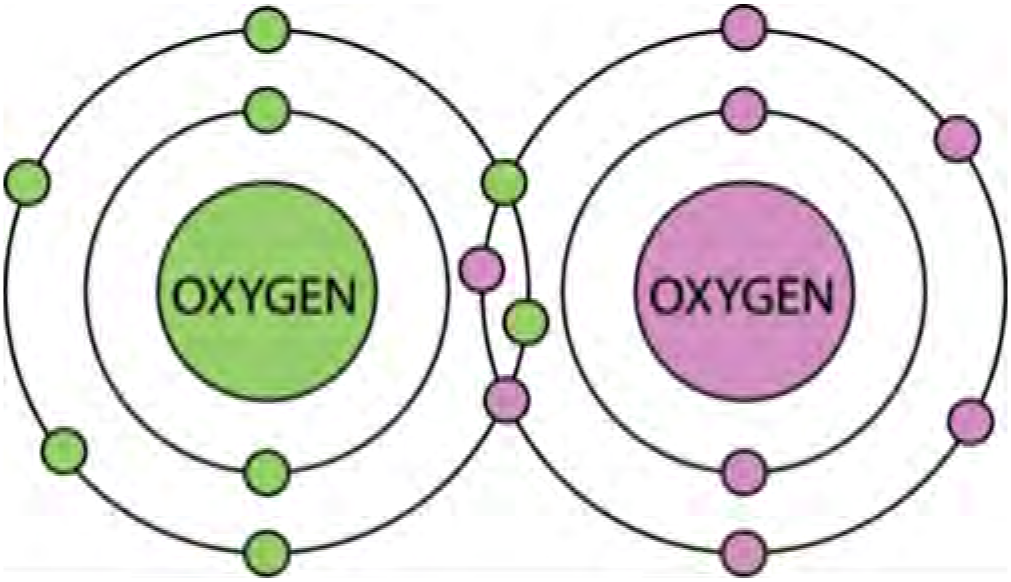


Image by Laura Guerin; CK-12 Foundation - Joy Sheng, CC-BY-NC 3.0

The two oxygen atoms share two pairs of electrons, so two covalent bonds hold the oxygen molecules together.

Properties of Covalent Compounds

Covalent compounds have properties very different from ionic compounds. Ionic compounds have high melting points causing them to be solid at room temperature, and conduct electricity when dissolved in water. Covalent compounds have low melting points and many are liquids or gases at room temperature. Whereas most ionic compounds are capable of dissolving in water, many covalent compounds do not. Also unlike ionic compounds, when covalent compounds are dissolved in water, they are not conductors of electricity; they are nonelectrolytes.

Bond Polarity

Electronegativity is defined as the ability of an atom to attract electrons when the atoms are in a compound. Electronegativities of elements are shown in the periodic table below.

The degree to which a given bond is ionic or covalent is determined by calculating the difference in electronegativity between the two atoms involved in the bond.

As an example, consider the bond that occurs between an atom of potassium and an atom of fluorine. Using the table, the difference in electronegativity is equal to 4.0 - 0.8 = 3.2. Since the difference in electronegativity is relatively large, the bond between the two atoms is ionic. Since the fluorine atom has a much larger attraction for electrons than the potassium atom does, the valence electron from the potassium atom is completely transferred to the fluorine atom. The diagram below shows how difference in electronegativity relates to the ionic or covalent character of a chemical bond.

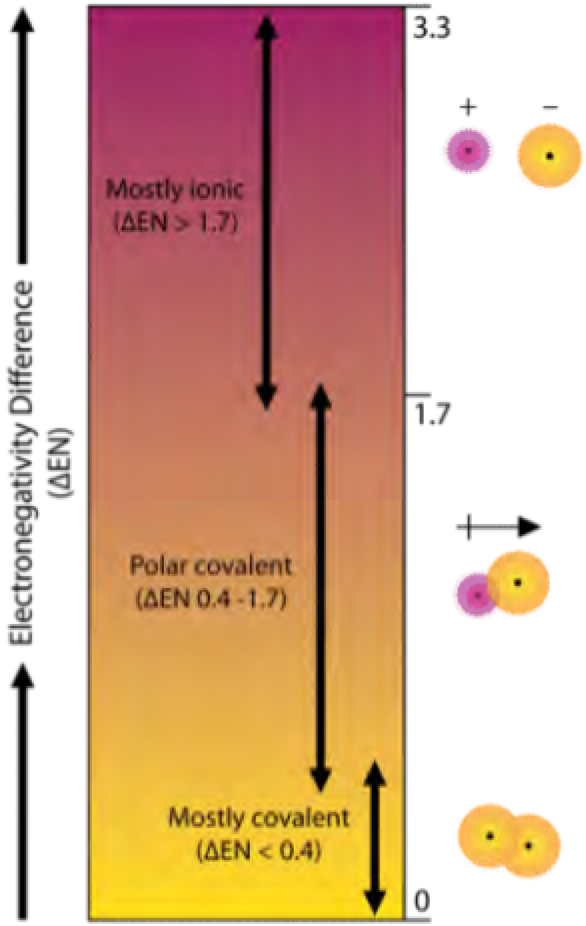


Image by Zachary Wilson, CK-12 Foundation, CC-BY-NC-SA 3.0

Bond type is predicated on the difference in electronegativity of the two elements involved in the bond.

Non-polar Covalent Bonds

A bond in which the electronegativity difference is less than 1.7 is considered to be mostly covalent in character. However, at this point we need to distinguish between two general types of covalent bonds. A non-polar covalent bond is a covalent bond in which the bonding electrons are shared equally between the two atoms. In a non-polar covalent bond, the distribution of electrical charge is balanced between the two atoms.

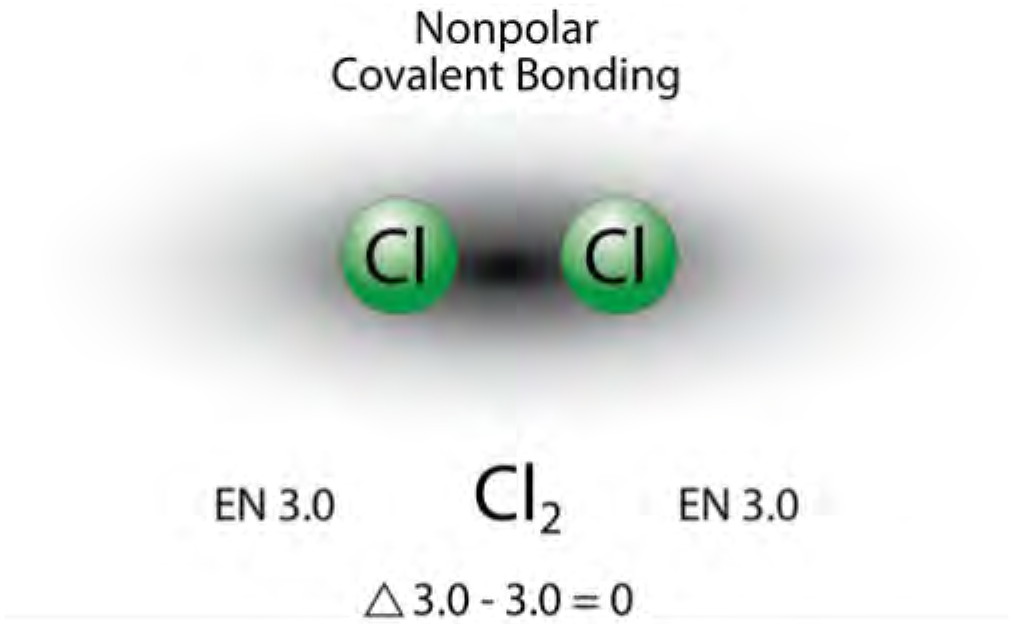


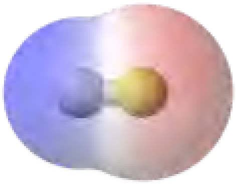
Image by Jodi So, CK-12 Foundation, CC-BY-NC-SA 3.0

A nonpolar covalent bond is one in which the distribution of electron density between the two atoms is equal.

The two chlorine atoms share a pair of electrons in the single covalent bond equally, and the electron density surrounding the Cl_2 molecule is symmetrical. Also note that molecules in which the electronegativity difference is very small (<0.4) are also considered non-polar covalent. An example would be a bond between chlorine and bromine .

($\Delta EN=3.0-2.8=0.2$)

Polar Covalent Bonds

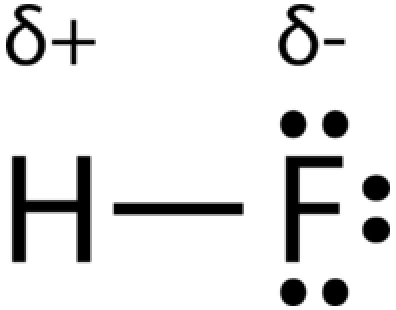


A bond in which the electronegativity difference between the atoms is between 0.4 and 1.7 is called a polar covalent bond. A polar covalent bond is a covalent bond in which the atoms have an unequal attraction for electrons and so the sharing is unequal. In a polar covalent bond, sometimes simply called a polar bond, the distribution of electrons around the molecule is no longer symmetrical.

In the polar covalent bond of HF, the electron density is unevenly distributed. There is a higher density (red) near the fluorine atom, and a lower density (blue) near the hydrogen atom.

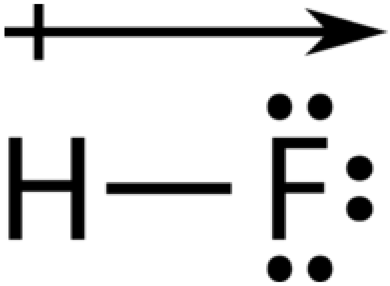
An easy way to illustrate the uneven electron distribution in a polar covalent bond is to use the Greek letter delta

(δ)



Use of δ to indicate partial charge.

The atom with the greater electronegativity acquires a partial negative charge, while the atom with the lesser electronegativity acquires a partial positive charge. The delta symbol is used to indicate that the quantity of charge is less than one. A crossed arrow can also be used to indicate the direction of greater electron density.



Use of crossed arrow to indicate polarity.

Putting It Together

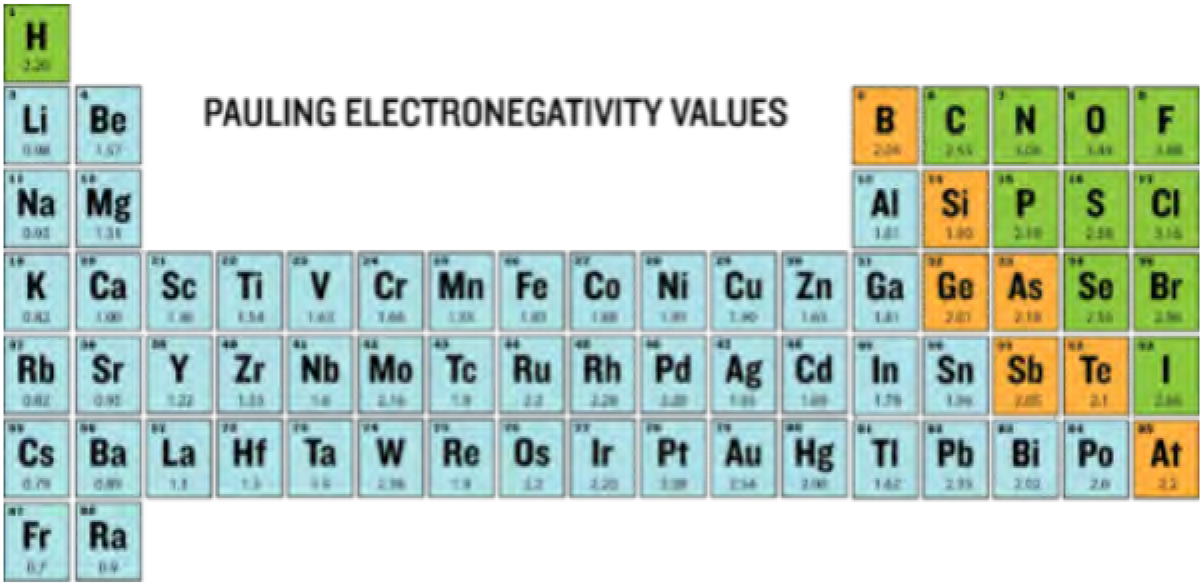


Image by Christopher Auyeung and Zachary Wilson, CK-12 Foundation, CC-BY-NC 3.0

Let us revisit this phenomenon:

This periodic table is showing electronegativity values for the periodic table.

1. Why is there a main group that is left out of the electronegativity values?
2. What type of bond would form when calcium and phosphorus react? What type of bond would form when carbon and phosphorus react?
3. How does electronegativity impact the type of chemical bond?

2.2 Structure and Properties (Chem.2.2)

Explore this Phenomenon

Salt (left) and sugar (right) under the microscope by Oleg Panichev, https://commons.wikimedia.org/wiki/File:Salt_(left)_and_sugar_(right)_under_the_microscope.jpg, CC-BY-SA

Imagine you have a hot drink that you want to sweeten with sugar. You can see two different white crystals. You know that one is table salt and one is sugar.

1. If you weren't allowed to taste the crystals, how would you figure out which one was which?
2. As you read the following section, think of possible tests you could conduct (besides tasting) to determine which white crystal is table salt and which white crystal is sugar.

Standard Chem.2.2

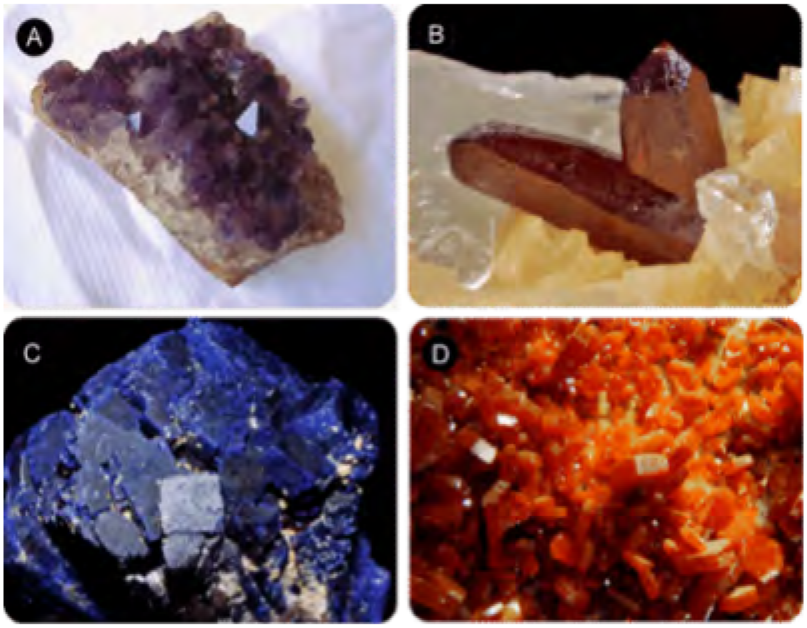
Plan and carry out an investigation to compare the properties of substances at the bulk scale and relate them to molecular structures. Emphasize using models to explain or describe the strength of electrical forces between particles. Examples of models could include Lewis dot structures or ball and stick models. Examples of particles could include ions, atoms, molecules, or networked materials (such as graphite). Examples of properties could include melting point and boiling point, vapor pressure, solubility, or surface tension. (PS1.A)

In this section, see if you can recognize how the structures of ionic substances and the structures of covalent substances could explain the properties and function of the substance.

Properties of Salt, NaCl

Sodium chloride, NaCl, is an ionic compound. It is made of one positively charged Sodium atom and one positively charged Chlorine atom. In the following sections, you will read about some of the other properties of ionic compounds.

Physical Properties of Ionic Compounds



In nature, the ordered arrangement of ionic solids gives rise to beautiful crystals. (A) Amethyst – a form of quartz, SiO_2, whose purple color comes from iron ions. (B) Cinnabar – the primary ore of mercury is mercury(II) sulfide, HgS. (C) Azurite – a copper mineral, $Cu_3(CO_3)_2(OH)_2$. D) Vanadinite – the primary ore of vanadium, $Pb_5(VO_4)_3Cl$.

Credit: (A) Mauro Cateb; (B) Parent Géry; (C) Parent Géry; (D) User:vassil/Wikimedia Commons
Source: (A) http://www.flickr.com/photos/mauroescriton/6544460363/ ; (B) http://commons.wikimedia.org/wiki/File:Cinabre_macl%C3%A9_%28Chine%29_.jpg ; (C) http://commons.wikimedia.org/wiki/File:Azurite_cristallis%C3%A9e_%28Chine%29_2_.jpg ; (D) http://commons.wikimedia.org/wiki/File:Vanadinite_21207.jpg
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What produces colored crystals?

The figure above shows just a few examples of the color and brilliance of naturally occurring ionic crystals. The regular and orderly arrangement of ions in the crystal lattice is responsible for the various shapes of these crystals, while transition metal ions give rise to the colors.

Physical Properties of Ionic Compounds

Melting Points

Because of the many simultaneous attractions between cations and anions that occur, ionic crystal lattices are very strong. The process of melting an ionic compound requires the addition of large amounts of energy in order to break all of the ionic bonds in the crystal. For example, sodium chloride has a melting point of about 800°C.

Shattering

Ionic compounds are generally hard, but brittle. Why? It takes a large amount of mechanical force, such as striking a crystal with a hammer, to force one layer of ions to shift relative to its neighbor. However, when that happens, it brings ions of the same charge next to each other (see Figure below). The repulsive forces between the like-charged ions cause the crystal to shatter. When an ionic crystal breaks, it tends to do so along smooth planes because of the regular arrangement of the ions.

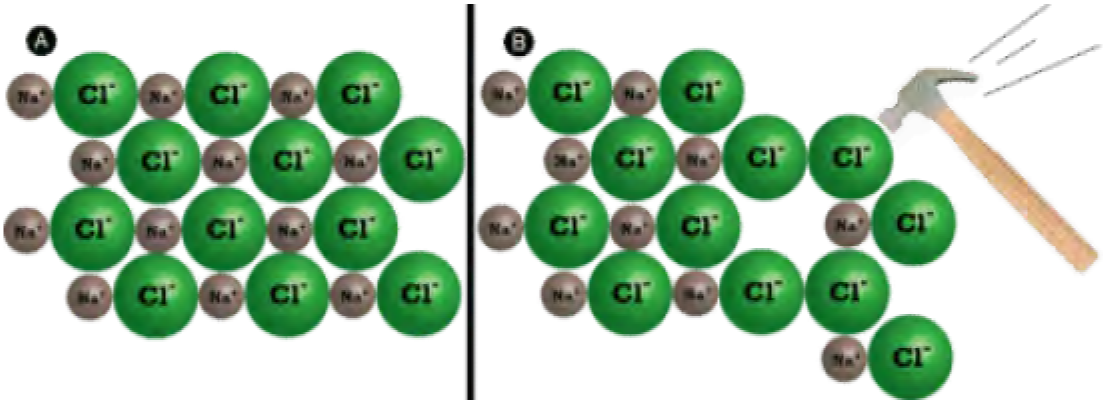
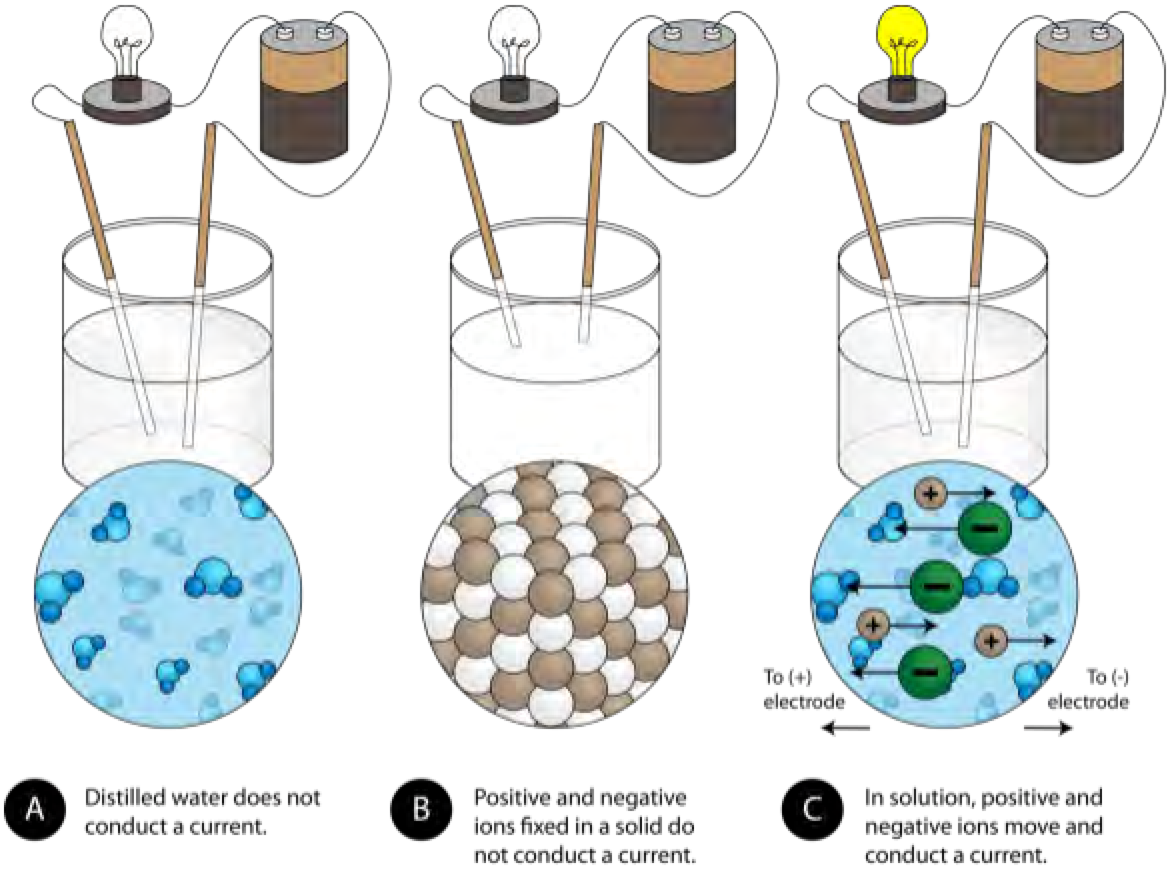


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

(A) The sodium chloride crystal is shown in two dimensions. (B) When struck by a hammer, the negatively-charged chloride ions are forced near each other and the repulsive force causes the crystal to shatter.

Conductivity

Another characteristic property of ionic compounds is their electrical conductivity. The figure below shows three experiments in which two electrodes that are connected to a light bulb are placed in beakers containing three different substances.



A Distilled water does not conduct a current.

B Positive and negative ions fixed in a solid do not conduct a current.

C In solution, positive and negative ions move and conduct a current.

Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

(A) Distilled water does not conduct electricity. (B) A solid ionic compound also does not conduct. (C) A water solution of an ionic compound conducts electricity well.

In the first beaker, distilled water does not conduct a current because water is a molecular compound. In the second beaker, solid sodium chloride also does not conduct a current. Despite being ionic and thus composed of charged particles, the solid crystal lattice does not allow the ions to move between the electrodes. Mobile charged particles are required for the circuit to be complete and the light bulb to light up. In the third beaker, the NaCl has been dissolved into the distilled water. Now the crystal lattice has been broken apart and the individual positive and negative ions can move. Cations move to one electrode, while anions move to the other, allowing electricity to flow (see Figure below). Melting an ionic compound also frees the ions to conduct a current. Ionic compounds conduct an electric current when melted or dissolved in water.

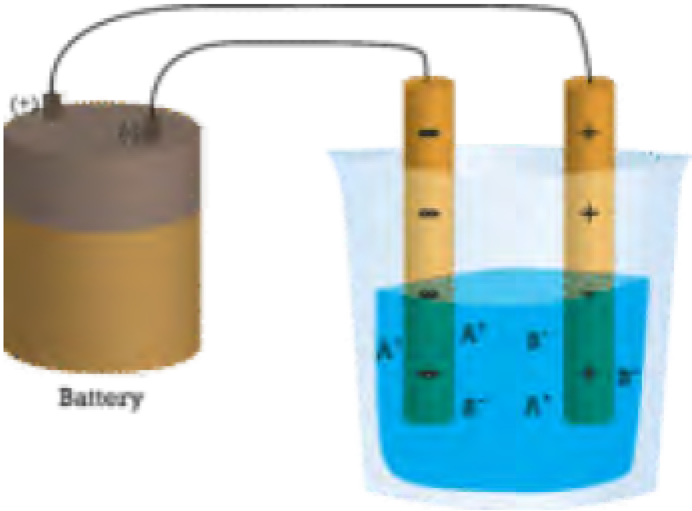


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

In an ionic solution, the A^+ ions migrate toward the negative electrode, while the B^- ions migrate toward the positive electrode.

What Are Nonmetals?

Nonmetals are elements that generally do not conduct electricity. They are one of three classes of elements (the other two classes are metals and metalloids.) Nonmetals are the second largest of the three classes after metals. They are the elements located on the right side of the periodic table.

Q: From left to right across each period (row) of the periodic table, each element has atoms with one more proton and one more electron than the element before it. How might this be related to the properties of nonmetals?

A: Because nonmetals are on the right side of the periodic table, they have more electrons in their outer energy level than elements on the left side or in the middle of the periodic table. The number of electrons in the outer energy level of an atom determines many of its properties.

Properties of Nonmetals

As their name suggests, nonmetals generally have properties that are very different from the properties of metals. Properties of nonmetals include a relatively low boiling point, which explains why many of them are gases at room temperature. However, some nonmetals are solids at room temperature, including the three pictured above, and one nonmetal—bromine—is a liquid at room temperature. Other properties of nonmetals are illustrated and described in the Figure below.

Solid nonmetals are generally dull and brittle like these pieces of iodine. Like other nonmetals, iodine lacks the luster of metals and will easily crack and crumble.

Iodine-sample by Benjah-bmm27, *public domain*
Sleeping Bag X by Artform Canada,
https://flic.kr/p/a2s9uP, CC-BY-NC-ND

Most nonmetals are poor conductors of heat. In fact, they are such poor conductors of heat that they are often used for insulation. For example, the down filling in this sleeping bag is full of pair, which consists primarily of the nonmetal bases oxygen and nitrogen. These gases prevent body heat from escaping to the cold outside air.

Reactivity of Nonmetals

Reactivity is how likely an element is to react chemically with other elements. Some nonmetals are extremely reactive, whereas others are completely nonreactive. What explains this variation in nonmetals? The answer is their number of valence electrons. These are the electrons in the outer energy level of an atom that are involved in interactions with other atoms. Let's look at two examples of nonmetals, fluorine and neon. Simple atomic models of these two elements are shown in the Figure below.

Q: Which element, fluorine or neon, do you predict is more reactive?

A: Fluorine is more reactive than neon. That's because it has seven of eight possible electrons in its outer energy level, whereas neon already has eight electrons in this energy level.

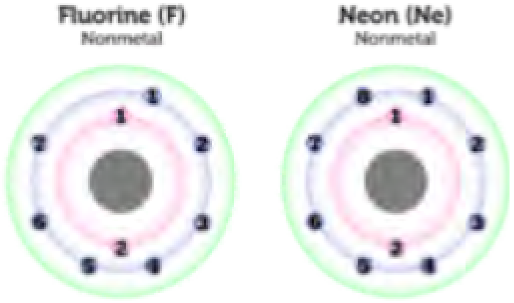


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

Although neon has just one more electron than fluorine in its outer energy level, that one electron makes a huge difference. Fluorine needs one more electron to fill its outer energy level in order to have the most stable arrangement of electrons. Therefore, fluorine readily accepts an electron from any element that is equally “eager” to give one up, such as the metal lithium or sodium. As a result, fluorine is highly reactive. In fact, reactions with fluorine are often explosive. Neon, on the other hand, already has a full outer energy level. It is already very stable and never reacts with other elements. It neither accepts nor gives up electrons. Neon doesn’t even react with fluorine, which reacts with all other elements except helium.

Why Most Nonmetals Cannot Conduct Electricity

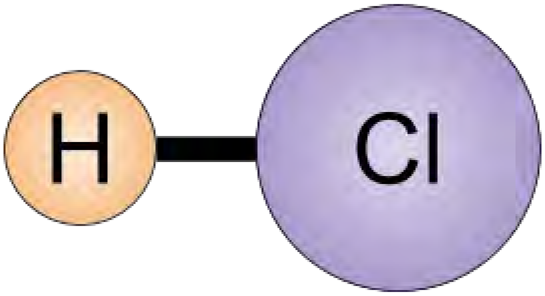
Like most other nonmetals, fluorine cannot conduct electricity, and its electrons explain this as well. An electric current is a flow of electrons. Elements that readily give up electrons (the metals) can carry an electric current because their electrons can flow freely. Elements that gain electrons instead of giving them up cannot carry electric current. They hold onto their electrons so they cannot flow

The burner on a gas stove burns with a pretty blue flame like the one pictured in the opening image. The fuel burned by most gas stoves is natural gas, which consists mainly of methane. Methane is a compound that contains only carbon and hydrogen. Like many other compounds that consist of just these two elements, methane is used for fuel because it burns very easily. Methane is an example of a covalent compound.

What Are Covalent Compounds?

Compounds that form from two or more nonmetallic elements, such as carbon and hydrogen, are called covalent compounds. In a covalent compound, atoms of different elements are held together in molecules by covalent bonds. These are chemical bonds in which atoms share valence electrons. The force of attraction between the shared electrons and the positive nuclei of both atoms holds the atoms together in the molecule. A molecule is the smallest particle of a covalent compound that still has the properties of the compound.

The largest, most complex covalent molecules have thousands of atoms. Examples include proteins and carbohydrates, which are compounds in living things. The smallest, simplest covalent compounds have molecules with just two atoms. An example is hydrogen chloride (HCl). It consists of one hydrogen atom and one chlorine atom, as you can see in the Figure below.



Properties of Covalent Compounds

The covalent bonds of covalent compounds are responsible for many of the properties of the compounds. Because valence electrons are shared in covalent compounds, rather than transferred between atoms as they are in ionic compounds, covalent compounds have very different properties than ionic compounds.

- Many covalent compounds, especially those containing carbon and hydrogen, burn easily. In contrast, many ionic compounds do not burn.
- Many covalent compounds do not dissolve in water, whereas most ionic compounds dissolve well in water.
- Unlike ionic compounds, covalent compounds do not have freely moving electrons, so they cannot conduct electricity.
- The individual molecules of covalent compounds are more easily separated than the ions in a crystal, so most covalent compounds have relatively low boiling points. This explains why many of them are liquids or gases at room temperature. You can compare the boiling points of some covalent and ionic compounds in the Table below.

Name of Compound (Chemical Formula)	Type of Compound	Boiling Point (°C)
Methane (CH_4)	covalent	-164
Nitrogen oxide (NO)	covalent	-152
Sodium chloride (NaCl)	ionic	1413
Lithium fluoride (LiF)	ionic	1676

Q: The two covalent compounds in the table are gases at room temperature, which is 20°C. For a compound to be a liquid at room temperature, what does its boiling point have to be?

A: To be a liquid at room temperature, a covalent compound has to have a boiling point higher than 20°C. Water is an example of a covalent compound that is a liquid at room temperature. The boiling point of water is 100°C.

Summary

- Covalent compounds contain two or more nonmetallic elements held together by covalent bonds, in which atoms share pairs of valence electrons. A molecule is the smallest particle of a covalent compound that still has the properties of the compound.
- Covalent bonds are responsible for many of the properties of covalent compounds. Covalent compounds have relatively low boiling points, cannot conduct electricity, and may not dissolve in water.

Putting It Together

Salt (left) and sugar (right) under the microscope by Oleg Panichev, https://commons.wikimedia.org/wiki/File:Salt_(left)_and_sugar_(right)_under_the_microscope.jpg, CC-BY-SA

Let us revisit the phenomenon: We now know that table salt is an ionic compound and sugar is a covalent compound.

1. Using your knowledge of the properties of ionic and covalent compounds design an experiment on how could you test if the white crystal is table salt or sugar.

2.3 Macromolecules (Chem.2.3)

Explore this Phenomenon

CC0 https://www.maxpixel.net/Wipe-Wet-Microfiber-Droplets-Towel-Car-Dry-3625683

Water forms clumps or beads on the surface of a car, but soaks into the towel.

1. Why does the water bead up on the car, but it soaks into the towel?
2. What difference in properties do you expect will cause this difference?

Standard Chem.2.3

Engage in argument supported by evidence that the functions of natural and designed macromolecules are related to their chemical structures. Emphasize the roles of attractive forces between and within molecules. Examples could include non-covalent interactions between base pairs in DNA allowing it to be unzipped for replication, the network of atoms in a diamond conferring hardness, or the nonpolar nature of polyester (PET) making it quick-drying. (PS1.A)

In this section, look for the ways in which the structure of atoms and molecules determine the properties and functions of those molecules. Pay attention to how the structure of molecules relates to the forces of attraction between those molecules and other molecules.

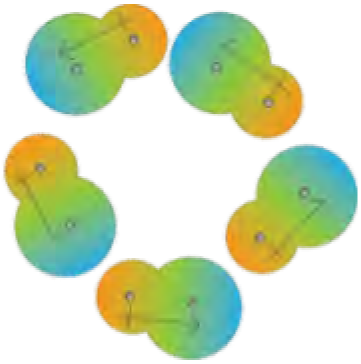
Forces of Attraction

The first type of force between molecules we will consider are called van der Waals forces, after Dutch chemist Johannes van der Waals (1837-1923). Van der Waals forces are the weakest intermolecular force and consist of dipole-dipole forces and dispersion forces.

Dipole-Dipole Forces

Dipole-dipole forces are the attractive forces that occur between polar molecules. A molecule of hydrogen chloride has a partially positive hydrogen atom and a partially negative chlorine atom. In a collection of many hydrogen chloride molecules, they will align themselves so that the oppositely charged regions of neighboring molecules are near each other.

Image by Jodi So, CK-12 Foundation, CC-BY-NC-SA 3.0



Dipole-dipole forces are a result of the attraction of the positive end of one dipole to the negative end of a neighboring dipole.

Dipole-dipole forces are similar in nature, but much weaker than ionic bonds.

London Dispersion Forces

Dispersion forces are also considered a type of van der Waals force and are the weakest of all intermolecular forces. They are often called London forces after Fritz London (1900-1954), who first proposed their existence in 1930. London dispersion forces are the intermolecular forces that occur between atoms and between nonpolar molecules as a result of the motion of electrons.

The electron cloud of a helium atom contains two electrons, which can normally be expected to be equally distributed spatially around the nucleus. However, at any given moment the electron distribution may be uneven, resulting in an instantaneous dipole. This weak and temporary dipole subsequently influences neighboring helium atoms through electrostatic attraction and repulsion. It induces a dipole on nearby helium atoms (see Figure below).

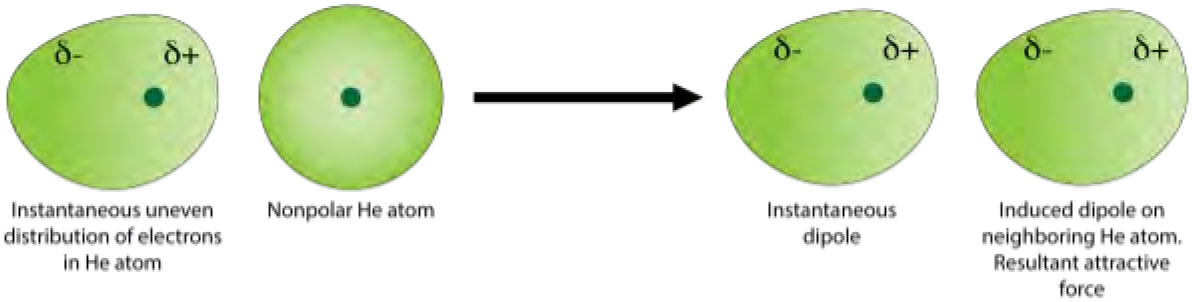
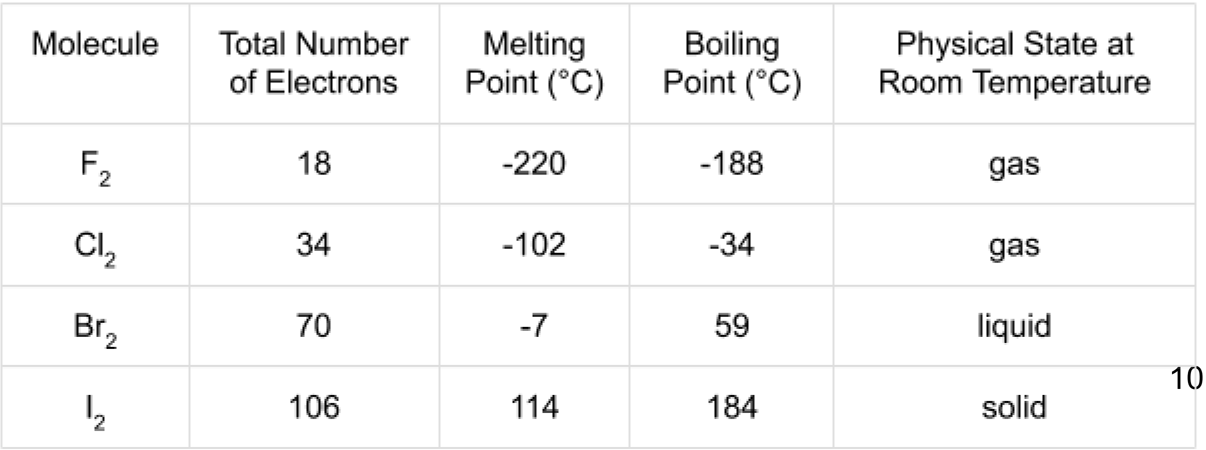


Image by Zachary Wilson, CK-12 Foundation, CC-BY-NC-SA 3.0

A short-lived or instantaneous dipole in a helium atom.

The instantaneous and induced dipoles are weakly attracted to one another. The strength of dispersion forces increases as the number of electrons in the atoms or nonpolar molecules increases.

The halogen group consists of four elements that all take the form of nonpolar diatomic molecules. Table below shows a comparison of the melting and boiling points for each.



Molecule	Total Number of Electrons	Melting Point (°C)	Boiling Point (°C)	Physical State at Room Temperature
F_2	18	-220	-188	gas
Cl_2	34	-102	-34	gas
Br_2	70	-7	59	liquid
I_2	106	114	184	solid

The dispersion forces are strongest for iodine molecules because they have the greatest number of electrons. The relatively stronger forces result in melting and boiling points which are the highest of the halogen group. These forces are strong enough to hold iodine molecules close together in the solid state at room temperature. The dispersion forces are progressively weaker for bromine, chlorine, and fluorine and this is illustrated in their steadily lower melting and boiling points. Bromine is a liquid at room temperature, while chlorine and fluorine are gases, whose molecules are much further apart from one another. Intermolecular forces are nearly nonexistent in the gas state, and so the dispersion forces in chlorine and fluorine only become measurable as the temperature decreases and they condense into the liquid state.

Hydrogen Bonding

The attractive force between water molecules is a dipole interaction. The hydrogen atoms are bound to the highly electronegative oxygen atom (which also possesses two lone pair sets of electrons, making for a very polar bond. The partially positive hydrogen atom of one molecule is attracted to the oxygen atom of a nearby water molecule (see Figure below).

A hydrogen bond in water occurs between the hydrogen atom of one water molecule and the lone pair of electrons on an oxygen atom of a neighboring water molecule.

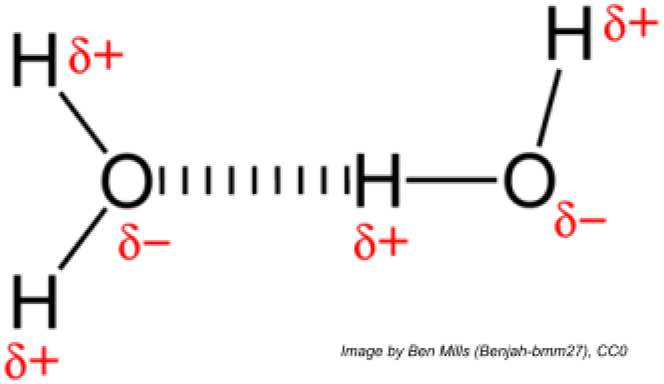


Image by Ben Mills (Benjah-bmm27), CC0

A hydrogen bond is an intermolecular attractive force in which a hydrogen atom that is covalently bonded to a small, highly electronegative atom is attracted to a lone pair of electrons on an atom in a neighboring molecule. Hydrogen bonds are very strong compared to other dipole interactions. The strength of a typical hydrogen bond is about 5% of that of a covalent bond.

Hydrogen bonding occurs only in molecules where hydrogen is covalently bonded to one of three elements: fluorine, oxygen, or nitrogen. These three elements are so electronegative that they withdraw the majority of the electron density in the covalent bond with hydrogen, leaving the H atom very electron-deficient. The H atom nearly acts as a bare proton, leaving it very attracted to lone pair electrons on a nearby atom.

The hydrogen bonding that occurs in water leads to some unusual, but very important properties. Most molecular compounds that have a mass similar to water are gases at room temperature. Because of the strong hydrogen bonds, water molecules are able to stay condensed in the liquid state. Figure below shows how the bent shape and two hydrogen atoms per molecule allows each water molecule to be able to hydrogen bond to two other molecules.

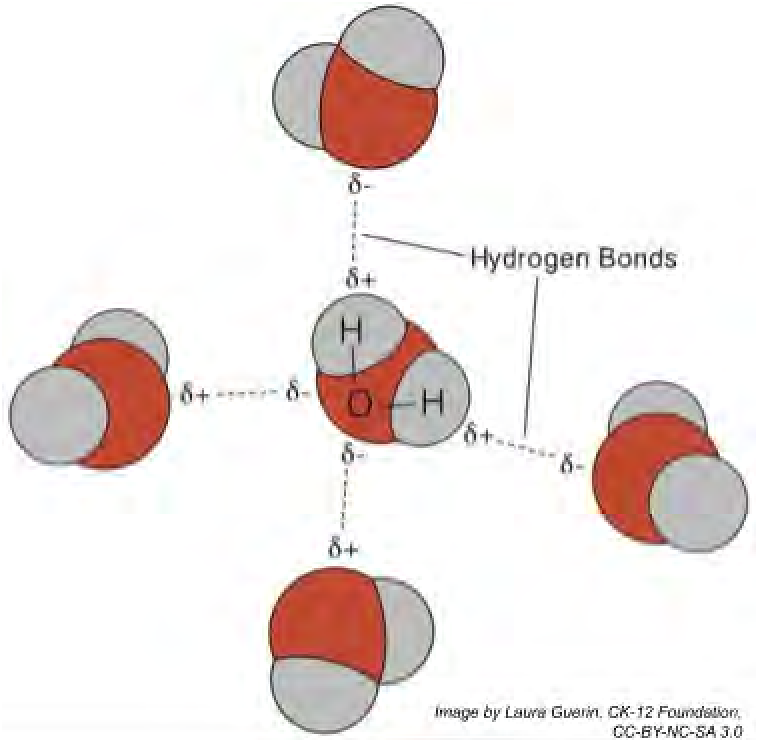
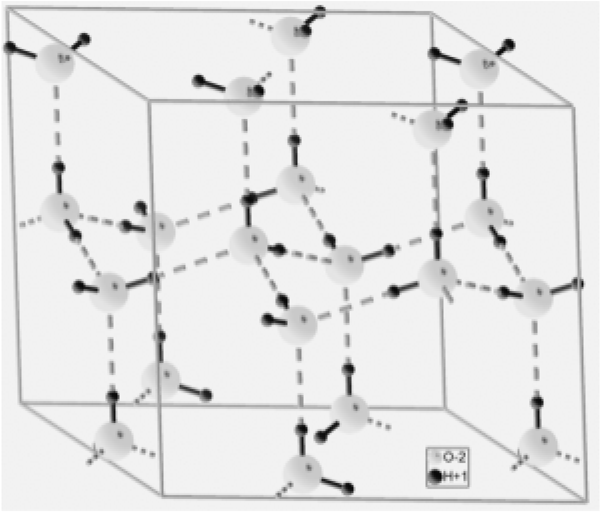


Image by Laura Guerin, CK-12 Foundation, CC-BY-NC-SA 3.0

Multiple hydrogen bonds occur simultaneously in water because of its bent shape and the presence of two hydrogen atoms per molecule.

In the liquid state, the hydrogen bonds of water can break and reform as the molecules flow from one place to another. When water is cooled, the molecules begin to slow down. Eventually, when water is frozen to ice, the hydrogen bonds become permanent and form a very specific network (see Figure below).



Adapted from image by Materialscientist/Wikimedia Commons, public domain

When water freezes to ice, the hydrogen bonding network becomes permanent. Each oxygen atom has an approximately tetrahedral geometry – two covalent bonds and two hydrogen bonds.

The bent shape of the molecules leads to gaps in the hydrogen bonding network of ice. Ice has an unusual property that its solid state is less dense than its liquid state. Ice floats in liquid water. Virtually all other substances are denser in the solid state than in the liquid state.

Putting It Together

CC0 https://www.maxpixel.net/Wipe-Wet-Microfiber-Droplets-Towel-Car-Dry-3625683

Let us revisit this phenomenon:

Water forms clumps or beads on the surface of a car, but soaks into the towel.

1. How do the intermolecular forces explain why the water soaks into the towel and beads on the car?
2. Would you expect nonpolar oil to have the same interaction between the car and the towel? Explain.

2.4 Synthetic Chemistry (Chem.2.4)

Explore this Phenomenon

Regular strength enteric coated aspirin tablets by ragesoss, https://en.wikipedia.org/wiki/Aspirin_exacerbated_respiratory_disease#/media/File:Regular_strength_enteric_coated_aspirin_tablets.jpg, CC-BY-SA 4.0

Aspirin was originally created from a compound found in the leaves of a plant which was then synthesized into what we now know as aspirin.

1. What is aspirin used for? What benefits does it have?
2. Why would we want to synthesize/make aspirin rather than trying to use the plant the original compound was from by itself?

Standard Chem.2.4

Evaluate **design solutions** where synthetic chemistry was used to solve a problem (cause and effect). *Define the problem, identify criteria and constraints, analyze available data on proposed solutions, and determine an optimal solution.* Emphasize the design of materials to control their properties through chemistry. Examples could include pharmaceuticals that target active sites, teflon to reduce friction on surfaces, or nanoparticles of zinc oxide to create transparent sunscreen. (PS1.A, ETS1.A, ETS1.B, ETS1.C)

In this section, look for information that describes the causes and effects of problems solved by aspirin. Identify the criteria and constraints that chemical engineers considered, analyze the data that shows that aspirin is effective in more than one context and compare aspirin made in a laboratory to natural methods for extracting salicylic acid.

What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of stems:

1. Identifying the problem and defining criteria and constraints.
2. Generating ideas for how to solve the problem. Engineers can use research, brainstorming and collaboration with others to come up with ideas for solutions and designs.
3. Build and then test the prototypes. Using data collected, the engineer can analyze how well the various prototypes meet the given criteria and constraints.
4. Evaluate what is needed to improve the leading design or devise a better one.

To design a solution to the problem, you will need to start by identifying the criteria and constraints. Then develop several possible solutions. Once you have several possible solutions, use the criteria and constraints to evaluate each. You should test the solution that will best meet the criteria and constraints, and then determine how to improve the solution, based on test results. Testing the solution may include modeling, working with materials, using mathematical relationships, etc.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

1. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).
2. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Which type of engineering task is utilized in this SEEd Standard?

Development of Aspirin

From ancient times, civilizations have known about the effectiveness of medicines made from willow and other plants. For example, Hippocrates in writings from around 400 BCE referred to the use of a tea made from this plant to reduce fevers. The use of this substance continued through the middle ages. Willow bark extract became recognized for its specific effects on fever, pain, and inflammation. By the nineteenth century pharmacists were experimenting with and prescribing a variety of chemicals related to salicylic acid, the active component of willow bark.

Due to its wide-spread use, chemists sought ways to synthetically produce salicylic acid and its derivative compounds. In 1853, Charles Gerhardt produced acetylsalicylic acid (today known as the active component of aspirin). Other chemists continued to analyze the compounds chemical structure and devised more efficient methods of synthesis. In 1897, scientists at the drug and dye firm Bayer began investigating acetylsalicylic acid as a less-irritating replacement for the original salicylate acid derived from willow bark. Bayer began synthesizing the compound in mass production and selling it around the world. They dubbed the compound as Aspirin.

Aspirin continues to be sold and used today as a pain reducer and anti-inflammatory. Additionally, trials show aspirin's efficacy as an anti-clotting agent used to prevent heart attacks and strokes.

Image by Peter H (Tama66), pixabay.com, CC0

Aspirin by Chanel Brasil, https://flic.kr/p/4qyU2X, CC-BY-NC-ND

Putting It Together

Image by S. Hermann & F. Richter (pixel2013), pixabay.com, CC0

Vitamin C can be found in citrus fruits

Image by Frank ([illegible]), pixabay.com, CC0

Plastic polymers

Image by Taken, pixabay.com, CC0

Teflon is used as a nonstick coating in pans

The development of aspirin and other pain relief products is one example of a natural compound that has been refined through synthetic chemistry for medicinal use. Other examples include the development of Ascorbic acid (Vitamin C), biotechnology products, polymers used in material science, nanoparticles of zinc oxide to create transparent sunscreen, and Teflon for cooking surfaces.

1. Pick a synthetic chemical and evaluate how it was used to solve a specific problem.

CHAPTER 3

Strand 3: Stability and Change in Chemical Systems

Chapter Outline

Image by Free-Photos, pixabay.com, CC0

Conservation of matter describes the cycling of matter and the use of resources. In both chemical and physical changes, the total number of each type of atom is conserved. When substances are combined, they may interact with each other to form a solution. The proportion of substances in a solution can be represented with concentration. In a chemical change, the atoms are rearranged by breaking and forming bonds to create different molecules, which may have different properties. Chemical processes can be understood in terms of the collisions of molecules and rearrangements of atoms. The rate at which chemical processes occur can be modified. In many situations, a dynamic and condition-dependent balance between a reaction and the reverse reaction determines the numbers of all types of molecules present. Chemists can control and design chemical systems to create desirable results, although sometimes there are also unintended consequences.

3.1 Solutions (Chem.3.1)

Explore this Phenomenon

Salt truck Milwaukee by Michael Pereckas,
https://commons.wikimedia.org/wiki/File:Salt_truck_Milwaukee.jpg, CC-BY

A dump truck carries salt to transport it to different locations in a city in the winter.

1. Why do some cold weather locations put salt on the roads?
2. Do you think the amount or concentration of salt being added will change the effect?
3. Do you think sugar would have the same effect?

Standard Chem.3.1

Use mathematics and computational thinking to analyze the distribution and proportion of particles in solution. Emphasize proportional reasoning and the impact of concentration on solution properties, rather than algorithmic calculations. Examples of concentrations affecting solutions could include the Beer-Lambert Law, colligative properties, or pH. (PS1.A)

In this section, pay attention to the number, size, and types (proportion) of particles that make up a solution. It is critical to recognize how changes in the number, size and type of particles will affect the properties of that solution.

Concentration of Solutions

When the weather is nice, many people begin to work on their yards and homes. For many projects, sand is needed as a foundation for a walk or to add to other materials. You could order up twenty million grains of sand and have people really stare at you. You could order by the pound, but that takes a lot of time weighing out. The best bet is to order by the yard, meaning a cubic yard. The loader can easily scoop up a yard of sand and put it directly in your truck.

Avogadro's Number

It certainly is easy to count bananas or to count elephants (as long as you stay out of their way). However, you would be counting grains of sugar from your sugar canister for a long, long time. Atoms and molecules are extremely small – far, far smaller than grains of sugar. Counting atoms or molecules is not only unwise, it is absolutely impossible. One drop of water contains about 10^{22} molecules of water. If you counted 10 molecules every second for 50 years without stopping you would have counted only 1.6×10^{10} molecules. Put another way, at that counting rate, it would take you over 30 trillion years to count the water molecules in one tiny drop.

Chemists needed a name that can stand for a very large number of items. Amedeo Avogadro (1776 - 1856), an Italian scientist, provided just such a number. He is responsible for the counting unit of measure called the mole. A mole (mol) is the amount of a substance that contains 6.02×10^{23} representative particles of that substance. The mole is the SI unit for the amount of a substance. Just like the dozen is 12, it is a name that stands for a number. There are therefore 6.02×10^{23} water molecules in a mole of water molecules. There also would be 6.02×10^{23} bananas in a mole of bananas, if such a huge number of bananas ever existed. This number, 6.02×10^{23} is called

Avogadro’s number. A mole of any substance contains Avogadro’s number (6.02×10^{23}) of representative particles.

Amedeo Avogadro, public domain

Italian scientist Amedeo Avogadro, whose work led to the concept of the mole as a counting unit in chemistry.

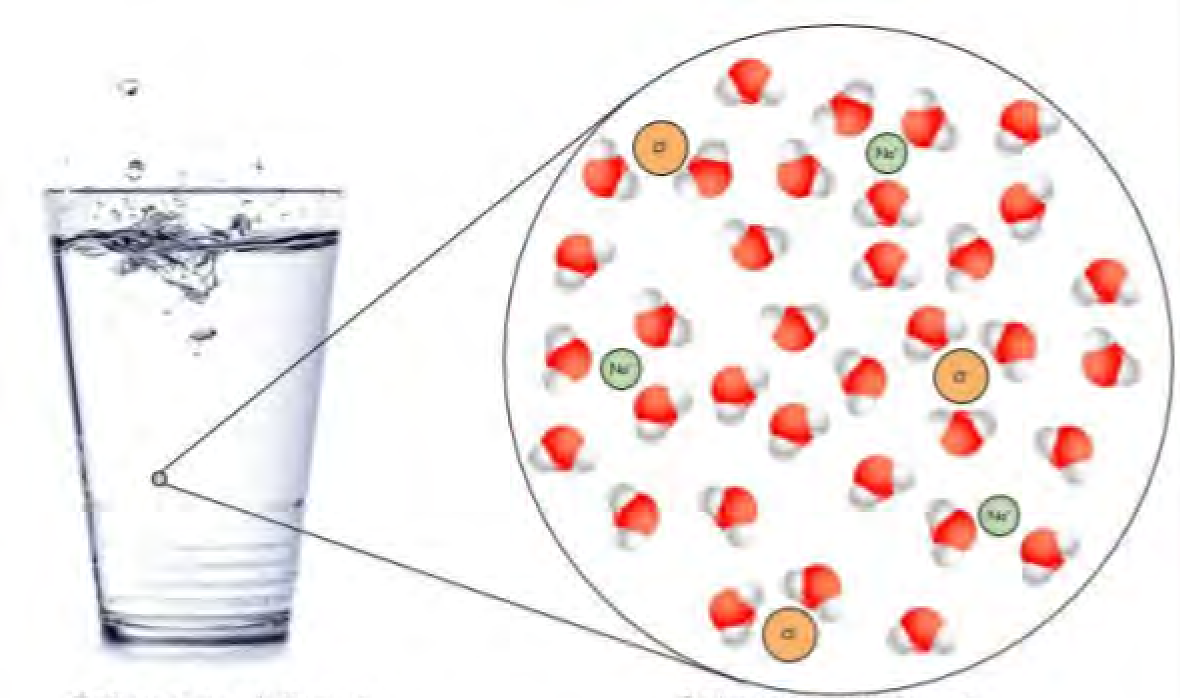
Close-up of mole by Michael David Hill, https://commons.wikimedia.org/wiki/File:Close-up_of_mole.jpg, CC-BY-SA

Examples of 1 Mole			
Substance	Symbol	Representative Particles	# of Particles in 1 mole
Carbon	C	Atom	6.02×10^{23}
Oxygen gas	O_2	Element	6.02×10^{23}
Water	H_2O	Molecule	6.02×10^{23}
Sodium Chloride	NaCl	Compound	6.02×10^{23}
Glucose	$C_6H_{12}O_6$	Molecule	6.02×10^{23}

Solutions

If you go to the store to buy apple juice you have many different options. If you buy juice concentrate some of the water has been removed and the directions on the back of the can tell you how much water to add to turn the concentrate into juice. Other bottles of apple juice may be ready to drink straight from the container.

Most juices are solutions (homogeneous mixtures of substances) . They are made of multiple compounds that are thoroughly mixed. Salt water is another example of a common household solution. The salt and the water are uniformly mixed at a particle level. Most of the time the different parts of the solution are not visible.



Salt water solution at macroscopic scale.

Salt water solution at molecular scale.

Tracy Poulsen, CC-BY

The water on the left looks like a pure substance, but it is actually a salt water solution. If you were to look at it on a molecular level (like the illustration on the right) you would see that the NaCl is evenly distributed.

The solvent and solute are the two parts of a solution. In the drawing above, H_2O is the solvent (the substance present in the greatest amount). The solute, (the substance present in the least amount) is the NaCl. When you are making a cup of hot chocolate, you take a teaspoon of cocoa powder and dissolve it in a cup of hot water. Since much less cocoa powder is used than water, the cocoa powder is the solute and water is the solvent.

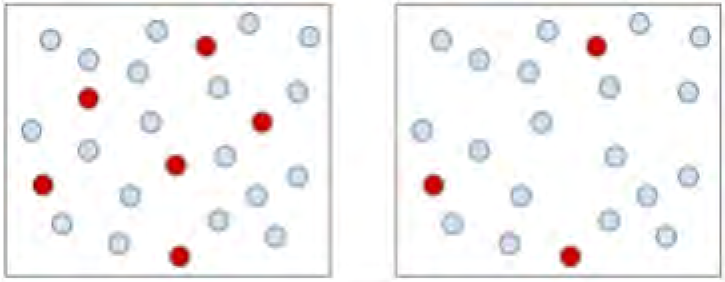
If you were to add a half teaspoon of salt to a cup of water, you would make a solution, but the composition of this solution would be different than if you tried to dissolve one-half cup of salt in a cup of water. What might happen? At this point, the solution has passed the limit of the amount of salt that can be dissolved in it, so it would no longer be a solution—salt would sink to the bottom of the container and never dissolve. As a result, solutions have a composition that can be varied up to a point. There are, however, limits to the amount of substance that can be dissolved into another substance and still remain evenly mixed.

Image by Dimitri Svetsikas, pixabay.com, CC0

If a scientist obtains a sample of water from the Atlantic Ocean and determined that the sample was about 3.5 percent dissolved salt the salt water from the Pacific Ocean would be approximately 3.5 percent also because it is a homogeneous mixture or a solution.

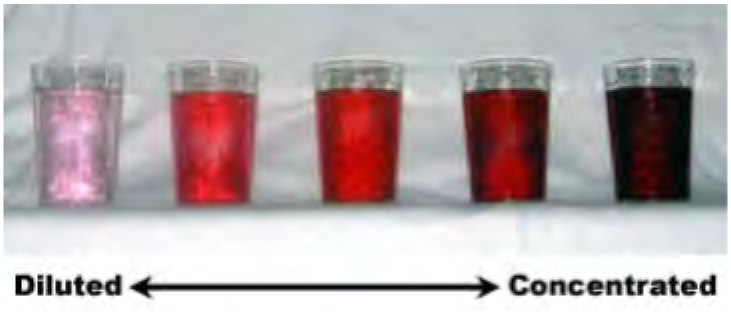
Concentration

Concentration (a measure of how much of a given substance is mixed with another substance) is one way that chemists describe solutions. Solutions can be said to be dilute or concentrated. A concentrated solution (one in which there is a large amount of solute in a given amount of solvent) has more particles dissolved in it than a dilute solution (one in which there is a small amount of solute in a given amount of solvent). A dilute solution is a concentrated solution that has been diluted or watered down. Think of the juice containers you buy in the grocery store. In order to make juice, you mix the frozen juice from inside these containers with about 3 or 4 times the amount of water. Therefore, you are diluting the concentrated juice. The terms “concentrated” and "dilute," however, only provide a qualitative way of describing concentration. In this chapter, we will explore some quantitative methods of expressing solution concentration.



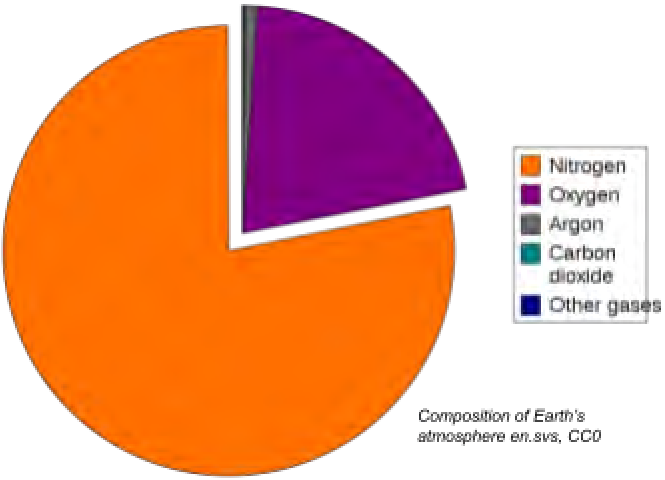
Tracy Poulsen, CC-BY

In this image, the solution on the left is more concentrated (more solute particles compared to solvent particles) than the solution on the right.



Dilution-concentration simple example, CC0

As you move from left to right, the solutions become more concentrated.



Composition of Earth's atmosphere en.svs, CC0

Air in the atmosphere is a gaseous solution. It is a mixture that contains mainly nitrogen and oxygen gases, with very small amounts of several other gases. The circle graph shows the composition of air. Because air is a solution, it is homogeneous. In other words, no matter where you go, the air always contains the same proportion of gases that are shown in the graph.

Molarity

Of all the quantitative measures of concentration, molarity – (the number of moles of solute per liter of solution) is the one used most frequently by chemists. The symbol given for molarity is M, or moles/liter.

$$\text{Molarity(M)}= \frac{Moles\,of\,solute}{liters\,of\,solution}$$

Example 1

A chemist wants to make a 2M solution of salt water. How could they do it?
Solution:

$$2M\,NaCl = \frac{2\,moles\,of\,NaCl}{1\,liter\,of\,solution}$$

- First find the molar mass of NaCl using a periodic table.
- Next, multiply the molar mass by 2 since the solution asks for 2 moles.
- Lastly, weigh out the 2 moles of NaCl then add water until the total solution reaches a volume of 1 liter.

Molarity is very easy to calculate when making 1 liter of solution, but often times chemists want to make more or less of a solution that has the same concentration. What if you want to make 2 liters of 2M NaCl (the same concentration as Example 1)? Since you are adding twice as much water, you would have to add twice as much NaCl. What if you want to make 0.5 L of 2M NaCl?

Example 2

What is the concentration, in mol/L, when 2.34 moles of NaCl has been dissolved in 500.0 mL of H_2O?
Solution:

The concentration of the NaCl solution is 4.68 mol/L or 4.68 M.

$$[NaCl] = \frac{2.34\,mol}{0.500\,liter} = 4.68\,M$$

Example 3

A solution is prepared by dissolving 42.23 g of NH_4Cl into enough water to make 500.0 mL of solution. Calculate its molarity.
Step 1: List the known quantities and plan the problem.

Known: mass = 42.23 g NH_4Cl; molar mass NH_4Cl = 53.50 g/mol; volume solution = 500.0 mL = 0.5000 L

Unknown: molarity =? M

The mass of the ammonium chloride is first converted to moles. Then the molarity is calculated by dividing by liters. Note the given volume has been converted to liters.
Step 2: Solve.

$$42.23g\, NH_4Cl \times \frac{1\, mol\, NH_4Cl}{53.50\, g\, NH_4Cl} = 0.789\, mol\, NH_4Cl$$

$$\frac{0.789\, mol\, NH_4Cl}{0.500\, L} = 1.579\, M\, NH_4Cl$$

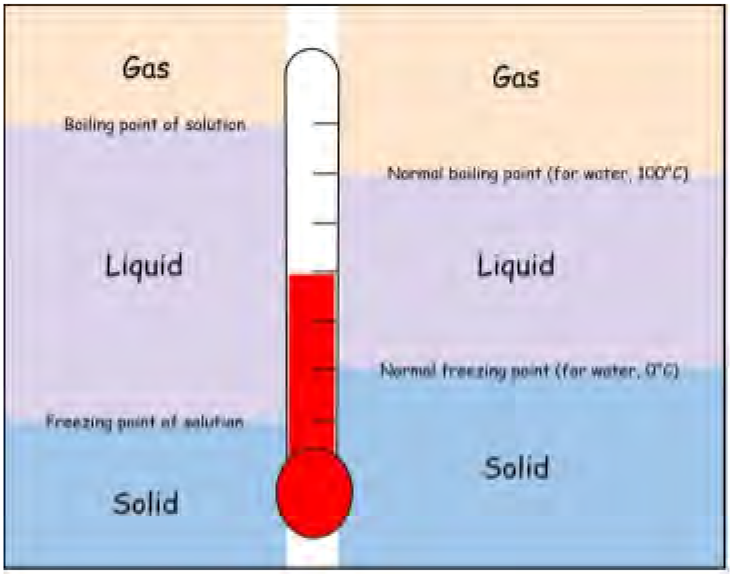
Step 3: Think about your result.

The molarity is 1.579 M, meaning that a liter of the solution would contain 1.579 mol NH_4Cl.

Colligative Properties

Any solute will lower the freezing point and raise the boiling point of any solvent. The greater the concentration of the solute the lower the freezing point and greater the boiling point.

You may have seen the trucks put salt on the roads when snow or ice is forecast. Why do they do that? When planes fly in cold weather, the planes need to be de-iced before liftoff. How is that done? It turns out that pure solvents differ from solutions in their boiling points and freezing points when a solute is added. Boiling and freezing point changes are both examples of colligative properties (properties of solutions that are due only to the number of particles in solution and not to the chemical properties of the solute).



Tracy Poulsen, CC-BY

Boiling Point Elevation

At 1 atm of pressure, pure water boils at 100ºC, but salt water does not. When table salt is added to water, the resulting solution has a higher boiling point than water alone.

Essentially, the solute particles take up space in the solvent, physically blocking some of the more energetic water molecules from escaping into the gas phase. This is true for any solute added to a solvent. Boiling point elevation (increase in a solvent's boiling temperature when a solute is added) is an example of a colligative property, meaning that the change in boiling point is related only to the number of solute particles in solution, regardless of what those particles are. A 0.20 m solution of table salt would have the same change in boiling point as a 0.20 m solution of KNO_3.

Freezing Point Depression

The effect of adding a solute to a solvent has the opposite effect on the freezing point of a solution as it does on the boiling point. Recall that the freezing point is the temperature at which a liquid changes to a solid. At a given temperature, if a substance is added to a solvent (such as water), the solute-solvent interactions prevent the solvent from going into the solid phase, requiring the temperature to decrease further before the solution will solidify. This is called freezing point depression (decrease in a solvent's freezing temperature when a solute is added).

Remember that colligative properties are due to the number of solute particles in the solution. Adding 10 molecules of sugar to a solvent will produce 10 solute particles in the solution. However, when the solute is an ionic compound, such as NaCl, adding 10 molecules of solute to the solution will produce 20 ions (solute particles) in the solution. Therefore, adding enough NaCl solute to a solvent to produce a 0.20 m solution will have twice the effect of adding enough sugar to a solvent to produce a 0.20 m solution.

Putting It Together

Salt truck Milwaukee by Michael Pereckas, https://commons.wikimedia.org/wiki/File:Salt_truck_Milwaukee.jpg, CC-BY

Let us revisit this phenomenon:

A dump truck carries salt to transport it to different locations in a city in the winter.

1. What colligative property is being demonstrated in this example?
2. How do colligative properties of a solution change as the concentration of salt goes from .10 m NaCl to .20 m NaCl?
3. Which would have the larger change in colligative properties a .20 m table salt solution or a .20 m sugar solution? Explain why.

3.2 Predicting Reactions (Chem.3.2)

Explore this Phenomenon

Adapted from IMG_3469 by eLLen, https://flic.kr/p/6PcmKE, CC-BY

Why is the silver dark? The pitcher shown above provides an example of tarnish, a chemical reaction caused when silver metal reacts with hydrogen sulfide gas produced by some industrial processes or as a result of decaying animal or plant materials. The tarnish can be removed using a number of polishes, but the process also removes a small amount of silver along with the tarnish.

This chemical reaction can be written like this:

$$2Ag + H_2S \rightarrow Ag_2S + H_2$$

1. What is happening to the atoms in the silver cup and the hydrogen sulfide gas that is causing the tarnish?
2. What is different between the right and left side of the chemical reaction? What is the same?

Standard Chem.3.2

Analyze data to identify patterns that assist in making predictions of the outcomes of simple chemical reactions. Emphasize patterns based on the outermost electrons of atoms, trends in the periodic table, and knowledge of chemical properties. Examples could include reactions between main group elements, combustion reactions, or reactions between Arrhenius acids and bases. (PS1.B)

In this section, look for patterns that allow us to classify chemical reactions. How do you know that a chemical change has occurred? Pay attention to the evidence for chemical reactions. How can you use those patterns to predict the outcomes of chemical reactions?

Reactions

Many chemical reactions can be classified as one of five basic types. Having a thorough understanding of these types of reactions will be useful for predicting the products of an unknown reaction. The five basic types of chemical reactions are combination, decomposition, single-replacement, double-replacement and combustion. Analyzing the reactants and products of a given reaction will allow you to place it into one of these categories. Some reactions will fit into more than one category.

Combination Reactions

A combination reaction is a reaction in which two or more substances combine to form a single new substance. Combination reactions can also be called synthesis reactions. The general form of a combination reaction is:

$A+B\rightarrow AB$

One combination reaction is two elements combining to form a compound. Solid sodium metal reacts with chlorine gas to produce solid sodium chloride.

$2Na(s)+Cl2(g)\rightarrow 2NaCl(s)$

Notice that in order to write and balance the equation correctly, it is important to remember the seven elements that exist in nature as diatomic molecules (H_2, N_2, O_2, F_2, Cl_2, Br_2 and I_2).

One sort of combination reaction that occurs frequently is the reaction of an element with oxygen to form an oxide. Metals and nonmetals both react readily with oxygen under most conditions. Magnesium reacts rapidly and dramatically when ignited, combining with oxygen from the air to produce a fine powder of magnesium oxide.

$2Mg(s)+O2(g)\rightarrow 2MgO(s)$

Sulfur reacts with oxygen to form sulfur dioxide.

$S(s)+O2(g)\rightarrow SO2(g)$

When nonmetals react with one another, the product is a molecular compound. Often, the nonmetal reactants can combine in different ratios and produce different products. Sulfur can also combine with oxygen to produce sulfur trioxide.

$2S(s)+3O2(g)\rightarrow 2SO3(g)$

Sample Problem: Combination Reactions

Potassium is a very reactive alkali metal that must be stored under oil in order to prevent it from reacting with air. Write the balanced chemical equation for the combination reaction of potassium with oxygen.

Step 1: Plan the problem.

Make sure formulas of all reactants and products are correct before balancing the equation. Oxygen gas is a diatomic molecule. Potassium oxide is an ionic compound and so its formula is constructed by the crisscross method. Potassium as an ion becomes K^{+}, while the oxide ion is O^{2-}.

Step 2: Solve.

The skeleton (unbalanced) equation:

$K(s)+O2(g)\rightarrow K2O(s)$

The equation is then easily balanced with coefficients.

$4K(s)+O2(g)\rightarrow 2K2O(s)$

Step 3: Think about your result.

The formulas are correct and the resulting combination reaction is balanced.

Practice Problems

1. Write a balanced equation for the combination reactions.

a) Al and O_2

b) Ca and Br_2

Decomposition Reactions

A decomposition reaction is a reaction in which a compound breaks down into two or more simpler substances. The general form of a decomposition reaction is:

$AB \rightarrow A+B$

Most decomposition reactions require an input of energy in the form of heat, light, or electricity.

Binary compounds are compounds composed of just two elements. The simplest kind of decomposition reaction is when a binary compound decomposes into its elements. Mercury(II) oxide, a red solid, decomposes when heated to produce mercury and oxygen gas.

$2HgO(s) \rightarrow 2Hg(l)+O2(g)$

Sample Problem: Decomposition Reactions

When an electric current is passed through pure water, it decomposes into its elements. Write a balanced equation for the decomposition of water.

Step 1: Plan the problem.

Water is a binary compound composed of hydrogen and oxygen. The hydrogen and oxygen gases produced in the reaction are both diatomic molecules.

Step 2: Solve.

The skeleton (unbalanced) equation:

$H2O(l) \rightarrow H2(g)+O2(g)$ via electrolysis

Balance the equation.

$2H2O(l) \rightarrow 2H2(g)+O2(g)$ via electrolysis

Step 3: Think about your result.

The products are elements and the equation is balanced.

Single-Replacement Reactions

A single-replacement reaction is a reaction in which one element replaces a similar element in a compound. The general form of a single-replacement (also called single-displacement) reaction is:

$A+BC\rightarrow AC+B$

In this general reaction, element *A* is a metal and replaces element *B*, also a metal, in the compound. When the element that is doing the replacing is a nonmetal, it must replace another nonmetal in a compound, and the general equation becomes:

$Y+XZ\rightarrow XY+Z$

Y is a nonmetal and replaces the nonmetal *Z* in the compound with *X*.

Metal Replacement

Magnesium is a more reactive metal than copper. When a strip of magnesium metal is placed in an aqueous solution of copper(II) nitrate, it replaces the copper. The products of the reaction are aqueous magnesium nitrate and solid copper metal.

$Mg(s)+Cu(NO3)2(aq)\rightarrow Mg(NO3)2(aq)+Cu(s)$

This subcategory of single-replacement reactions is called a metal replacement reaction because it is a metal that is being replaced (copper).

Hydrogen Replacement

Many metals react easily with acids and, when they do so, one of the products of the reaction is hydrogen gas. Zinc reacts with hydrochloric acid to produce aqueous zinc chloride and hydrogen (figure below).

$Zn(s)+2HCl(aq)\rightarrow ZnCl2(aq)+H2(g)$

In a hydrogen replacement reaction, the hydrogen in the acid is replaced by an active metal.

[illegible]

Zinc metal reacts with hydrochloric acid to give off hydrogen gas in a single-replacement reaction.

Some metals are so reactive that they are capable of replacing the hydrogen in water. The products of such a reaction are the metal hydroxide and hydrogen gas. All group 1 metals undergo this type of reaction. Sodium reacts vigorously with water to produce aqueous sodium hydroxide and hydrogen (figure below).

$2Na(s)+2H2O(l)\rightarrow 2NaOH(aq)+H2(g)$

Large Sodium Explosion, CC0

Pictured here is about 3 pounds of sodium metal reacting with water. Sodium metal reacts vigorously when dropped into a container of water, giving off hydrogen gas. A large piece of sodium will often generate so much heat that the hydrogen will ignite.

Halogen Replacement

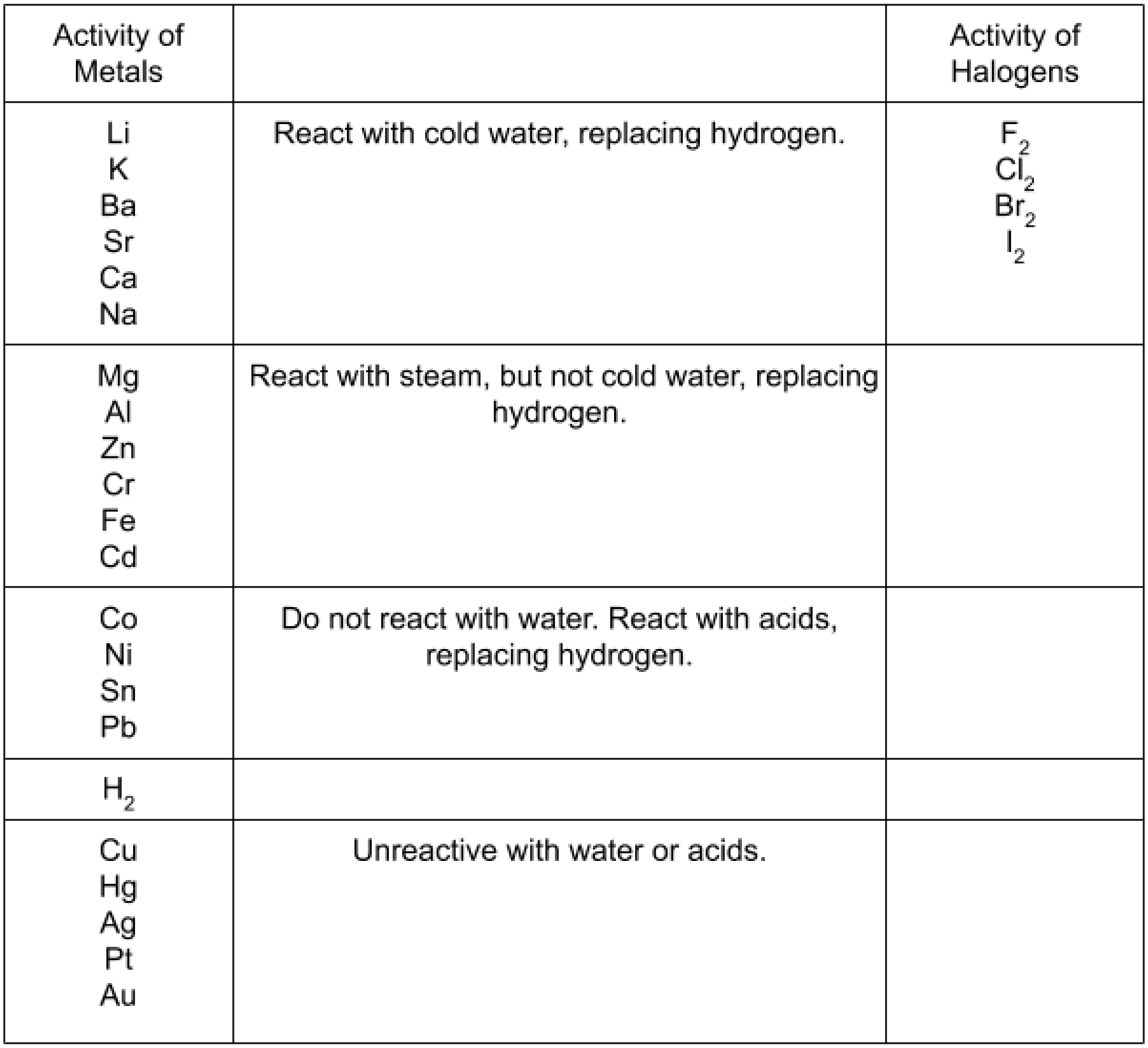
The element chlorine reacts with an aqueous solution of sodium bromide to produce aqueous sodium chloride and elemental bromine.

$Cl2(g)+2NaBr(aq)\rightarrow 2NaCl(aq)+Br2(l)$

The reactivity of the halogen group (group 17) decreases from top to bottom within the group. Fluorine is the most reactive halogen, while iodine is the least. Since chlorine is above bromine, it is more reactive than bromine and can replace it in a halogen replacement reaction.

The Activity Series

Single-replacement reactions only occur when the element that is doing the replacing is more reactive than the element that is being replaced. Therefore, it is useful to have a list of elements in order of their relative reactivities. The activity series is a list of elements in decreasing order of their reactivity. Since metals replace other metals, while nonmetals replace other nonmetals, they each have a separate activity series. Listed below (table below) is an activity series of most common metals, and of the halogens.



Activity of Metals		Activity of Halogens
Li K Ba Sr Ca Na	React with cold water, replacing hydrogen.	F_2 Cl_2 Br_2 I_2
Mg Al Zn Cr Fe Cd	React with steam, but not cold water, replacing hydrogen.	
Co Ni Sn Pb	Do not react with water. React with acids, replacing hydrogen.	
H_2		
Cu Hg Ag Pt Au	Unreactive with water or acids.	

For a single-replacement reaction, a given element is capable of replacing an element that is below it in the activity series. This can be used to predict if a reaction will occur. Suppose that small pieces of the metal nickel were placed into two separate aqueous solutions: one of iron(III) nitrate and one of lead(II) nitrate. Looking at the activity series, we see that nickel is below iron, but above lead. Therefore, the nickel metal will be capable of replacing the lead in a reaction, but will not be capable of replacing iron.

$Ni(s)+Pb(NO3)2(aq) \rightarrow Ni(NO3)2(aq)+Pb(s)$

$Ni(s)+Fe(NO3)3(aq) \rightarrow NR$(no reaction)

In the descriptions that accompany the activity series of metals, a given metal is also capable of undergoing the reactions described below that section. For example, lithium will react with cold water, replacing hydrogen. It will also react with steam and with acids, since that requires a lower degree of reactivity.

Sample Problem: Single-Replacement Reactions

Use the activity series to predict if the following reactions will occur. If not, write NR. If the reaction does occur, write the products of the reaction and balance the equation.

1. $Al(s)+Ba_3N_2(aq)\rightarrow$

2. $Sr(s)+HCl(aq)\rightarrow$

Step 1: Plan the problem.

For 1, compare the placements of aluminum and barium on the activity series. For 2, compare the placements of strontium and hydrogen.

Step 2: Solve.

Since aluminum is below barium, it is not capable of replacing it and a reaction will not occur.

$Al(s)+Ba_3N_2(aq)\rightarrow NR$

Since strontium is above hydrogen, it is capable of replacing hydrogen in a reaction with an acid. The strontium is now going to be bonded to chlorine. Take care to write the correct formulas for the products before balancing the equation. The balanced equation is:

$Sr(s)+2HCl(aq)\rightarrow SrCl_2(aq) + H_2(g)$

Step 3: Think about your result.

Double-Replacement Reactions

A double-replacement reaction is a reaction in which the positive and negative ions of two ionic compounds exchange places to form two new compounds. The general form of a double-replacement (also called double-displacement) reaction is:

$AB+CD\rightarrow AD+CB$

In this reaction, *A* and *C* are positively-charged cations, while *B* and *D* are negatively-charged anions. Double-replacement reactions generally occur between substances in aqueous solution. In order for a reaction to occur, one of the products is usually a solid precipitate, a gas, or a molecular compound such as water.

Examples:

$2KI(aq)+Pb(NO3)2(aq)\rightarrow 2KNO3(aq)+PbI2(s)$

$Na2S(aq)+2HCl(aq)\rightarrow 2NaCl(aq)+H2S(g)$

$HCl(aq)+NaOH(aq)\rightarrow NaCl(aq)+H2O(l)$

Sample Problem: Double-Replacement Reactions

Write a complete and balanced chemical equation for the following double-replacement reactions. One product is indicated as a guide.

1. $NaCN(aq)+HBr(aq)\rightarrow$(hydrogen cyanide gas is formed)

2. $(NH4)2SO4(aq)+Ba(NO3)2(aq)\rightarrow$(a precipitate of barium sulfate forms)

Step 1: Plan the problem.

In 1, the production of a gas drives the reaction. In 2, the production of a precipitate drives the reaction. In both cases, use the ionic charges of both reactants to construct the correct formulas of the products.

Step 2: Solve.

1. The cations of both reactants are 1+ charged ions, while the anions are 1− charged ions. After exchanging partners, the balanced equation is:

$NaCN(aq)+HBr(aq)\rightarrow NaBr(aq)+HCN(g)$

2. Ammonium ion and nitrate ion are 1+ and 1− respectively, while barium and sulfate are 2+ and 2−. This must be taken into account when exchanging partners and writing the new formulas. Then, the equation is balanced.

$(NH4)2SO4(aq)+Ba(NO3)2(aq)\rightarrow 2NH4NO3(aq)+BaSO4(s)$

Step 3: Think about your result.

Combustion Reactions

A combustion reaction is a reaction in which a substance reacts with oxygen gas, releasing energy in the form of light and heat. Combustion reactions must involve O_2 as one reactant. Many combustion reactions occur with a hydrocarbon, a compound made up solely of carbon and hydrogen. The products of the combustion of hydrocarbons are carbon dioxide and water. Many hydrocarbons are used as fuel because their combustion releases very large amounts of heat energy. Propane (C_3H_8) is a gaseous hydrocarbon that is commonly used as a fuel source in gas grills.

$C3H8(g)+5O2(g)\rightarrow 3CO2(g)+4H2O(g)$

Practice Problem: Combustion Reactions

Ethanol can be used as a fuel source in an alcohol lamp. The formula for ethanol is C_2H_5OH. Write the balanced equation for the combustion of ethanol.

Step 1: Plan the problem.

Ethanol and oxygen are the reactants. As with a hydrocarbon, the products of the combustion of an alcohol are carbon dioxide and water.

Step 2: Solve.

Write the skeleton equation:

$C2H5OH(l)+O2(g)\rightarrow CO2(g)+H2O(g)$

Balance the equation.

$C2H5OH(l)+3O2(g)\rightarrow 2CO2(g)+3H2O(g)$

Step 3: Think about your result.

Combustion reactions must have oxygen as a reactant. Note that the water that is produced is in a gas state rather than the liquid state because of the high temperatures that accompany a combustion reaction.

Putting It Together

Adapted from IMG_3469 by eLLen, https://flic.kr/p/6PcmKE, CC-BY

Let us revisit this phenomenon:

Why is the silver dark? The pitcher shown above provides an example of tarnish, a chemical reaction caused when silver metal reacts with hydrogen sulfide gas produced by some industrial processes or as a result of decaying animal or plant materials. The tarnish can be removed using a number of polishes, but the process also removes a small amount of silver along with the tarnish.

This chemical reaction can be written like this:

$$2Ag + H_2S \rightarrow Ag_2S + H_2$$

1. Which product is the tarnish?
2. What type of reaction is represented above?
3. Would you expect the same type of reaction for something made from gold (Au)? Why or why not?

3.3 Macroscopic Changes (Chem.3.3)

Explore this Phenomenon

Magnesium ribbon burning by Capt. John Yossarian, https://commons.wikimedia.org/wiki/File:Magnesium_ribbon_burning.jpg, CC-BY-SA

Magnesium is a metal and oxygen is a nonmetal. In this picture, magnesium is burning in the presence of oxygen.

1. What properties do metals like magnesium have?
2. What properties do nonmetals like oxygen have?
3. How do we know that chemical change is occurring?
4. As you read the following section, think about what other investigations you could conduct to observe and collect data on chemical change.

Standard Chem.3.3

Plan and carry out an investigation to observe the change in properties of substances in a chemical reaction to relate the macroscopically observed properties to the molecular level changes in bonds and the symbolic notation used in chemistry. Emphasize that the visible macroscopic changes in chemical reactions are a result of changes on the molecular level. Examples of observable properties could include changes in color or the production of a solid or gaseous product. (PS1.B)

In this section, look for ways in which substances change through chemical reactions to create more stable compounds. Pay attention to how chemical change occurs in both natural and man made systems. Also, look for the rules for writing chemical equations that scientists use to systematically describe compounds and chemical reactions.

What is a Chemical Reaction?

Image by AnnBehemotik, pixabay.com, CC0

Yummy! S'mores are on the way! Did you ever toast marshmallows over a campfire? The sweet treats singe on the outside and melt on the inside. Both the fire and toasted marshmallows are evidence of chemical changes. In the process of burning, the wood changes to ashes and gases, and the outside of the marshmallow turns brown and crispy. That's because burning is a chemical change.

In this unit, you'll learn about many types of chemical changes, including how they occur and why you can't live without them. A chemical reaction (a process in which some substances change into different substances) occur around us and in us all the time. Whenever substances go through a change in which different types of molecules or particles are present at the end of the change a chemical reaction has occurred.

Reactants (the starting materials in a chemical reaction) are converted into products (the ending materials in a chemical reaction). Reactants and products can be elements or compounds. Chemical reactions are represented by chemical equations, like the one below, in which reactants (on the left) are connected by an arrow to products (on the right).

$$\mathbf{Zn+Cu(NO_3)_2 \rightarrow Zn(NO_3)_2 + Cu,\ Reactants \rightarrow Products}$$

Chemical reactions may occur quickly or slowly. Look at the two pictures in the figure. Both represent chemical reactions. In the picture on the left, a reaction inside a fire extinguisher causes foam to shoot out of the extinguisher. This reaction occurs almost instantly. In the picture on the right, a reaction causes the iron tool to turn to rust. This reaction occurs very slowly. In fact, it might take many years for all of the iron in the tool to turn to rust.

A sailor uses a portable fire extinguisher, public domain

Rust screw by Paulnasca, https://commons.wikimedia.org/wiki/File:Rust_screw.jpg, CC-BY

Breaking and Making Chemical Bonds

The reactants and products in a chemical reaction contain the same atoms, but they are rearranged during the reaction. As a result, the atoms end up in different combinations in the products. This makes the products new substances that are chemically different from the reactants.

Consider the example of the reaction between sodium and chlorine to make sodium chloride (table salt). Sodium is a metal that is shiny, an excellent conductor of electric current, and reacts violently with water. Chlorine is a poisonous green gas. When sodium and chlorine are chemically combined to form sodium chloride, the product has an entirely new set of properties. Sometimes we sprinkle salt (sodium chloride) on our food. The properties of the products are different than the properties of the reactants. We would not put salt on our potato chips if it had the same explosive and deadly properties as the original reactants.

Adapted from

Adapted from

Adapted from image by nuno Glätsch, pixabay.com

Watch the animation of a similar chemical reaction at the following URL. Can you identify the reactants and the product in the reaction?

- http://go.uen.org/b6V

Evidence of Chemical Change

Adapted from "Alistair" by Nigel Wade, https://flic.kr/p/3gz1tj, CC-BY-SA

Look at the man's hair in the photo. It has obviously changed color. The process in which this occurred involved chemical reactions. How do you know that chemical reactions have occurred? The change in color is the most obvious clue.

Chemical reactions occur when bonds are broken and/or formed as the reactants are changed into the products. However, we can't directly observe the breaking and forming of bonds. We have to look for other evidence of chemical change. Because the products of a chemical reaction have different properties than the reactants, there are several observations that we can make to help us know when a chemical change has occurred.

- Change of color
- Light is given off
- Change in temperature – Heat is released or absorbed during the reaction
- Production of a gas – Gas bubbles are released during the reaction
- Production of a solid – A solid settles out of a liquid solution. The solid is called a precipitate

Examples of Chemical Reactions

Look carefully at the figures below. All of the photos demonstrate chemical reactions. For each photo, identify a sign that one or more chemical reactions have taken place.

You can see other examples of chemical reactions at this URL:

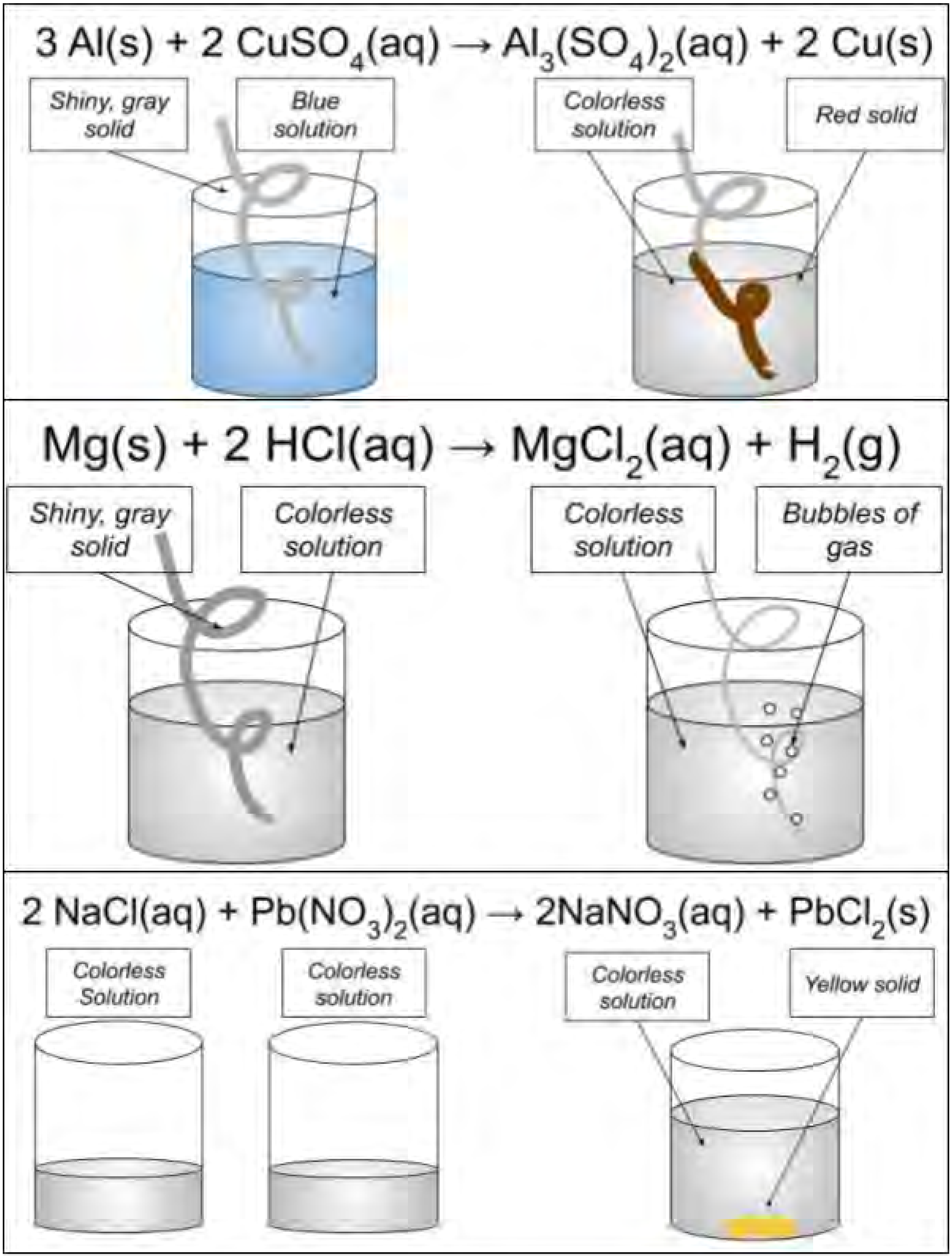
- http://go.uen.org/b6W

A burning campfire can warm you up on a cold day. *(pixabay.com, CC0)*

Dissolving an antacid tablet in water produces a fizzy drink. *(Alka Seltzer by Ebarella_R, https://flic.kr/p/Js9ZE2, CC-BY*

Adding acid to milk produces curds of cottage cheese. *(pixabay.com, CC0)*

These vividly colored maple leaves were all bright green during the summer. Every fal leaves of maple trees change to brilliant red, orange, and yellow colors. Maple leaves change color because of chemical reactions. *(pixabay.com, CC0)*



$3\ Al(s) + 2\ CuSO_4(aq) \rightarrow Al_3(SO_4)_2(aq) + 2\ Cu(s)$

$Mg(s) + 2\ HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

$2\ NaCl(aq) + Pb(NO_3)_2(aq) \rightarrow 2NaNO_3(aq) + PbCl_2(s)$

Images by Tracy Poulsen, CC-BY

Summary

- All chemical reactions involve both reactants and products. Reactants are substances that start a chemical reaction, and products are substances that are produced in the reaction.
- A chemical reaction can be represented by the general chemical formula: Reactants→Products
- Bonds break and reform during chemical reactions. Reactants and products contain the same atoms, but they are rearranged during the reaction, so reactants and products are different substances.
- Potential signs that chemical reactions have occurred include a change in color, change in temperature, production of a gas, and production of a solid precipitate.

Writing Chemical Equations

Even though chemical compounds are broken up to form new compounds during a chemical reaction, atoms in the reactants do not disappear, nor do new atoms appear to form the products. In chemical reactions, atoms are never created or destroyed. The same atoms that were present in the reactants are present in the products. The atoms are merely re-organized into different arrangements. In a complete chemical equation, the two sides of the equation must be balanced. That is, in a balanced chemical equation, the same number of each atom must be present on the reactant and product sides of the equation.

Chemical reactions are represented by chemical equations. Consider a simple chemical reaction, the burning of methane. In this reaction, methane (CH_4) combines with oxygen (O_2) in the air and produces carbon dioxide (CO_2) and water vapor (H_2O). The reaction is represented by the following chemical equation:

$$\mathbf{CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O}$$

This balanced chemical equation can be read as 1 mole of CH_4 plus 2 moles of O_2 reacts to form 1 mole of CO_2 and 2 moles of H_2O.

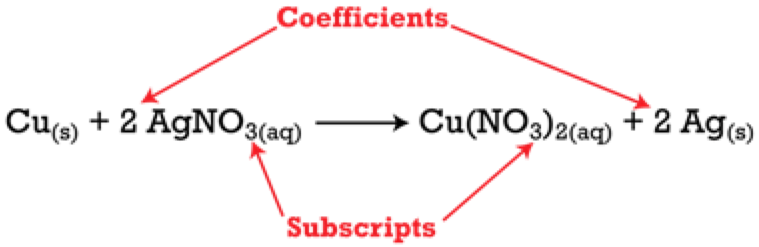
This equation shows that one molecule of methane combines with two molecules of oxygen to produce one molecule of carbon dioxide and two molecules of water vapor. All chemical equations must be balanced. This means that the same number of each type of atom must appear on both sides of the arrow. This chemical equation is balanced because there is one carbon atom, four hydrogen atoms, and four oxygen atoms on the left side of the arrow AND there is one carbon atom, four hydrogen atoms, and four oxygen atoms on the right side of the arrow.

Balancing Equations

The process of writing a balanced chemical equation involves three steps. As a beginning chemistry student, you will not know whether or not two given compounds will react or not. Even if you saw them react, you would not know what the products are without running any tests to identify them. Therefore, for the time being, you will be told both the reactants and products in any equation you are asked to balance.

- Step 1: Identify the reactants and products
- Step 2: Write the formulas for all the reactants and products
- Step 3: Adjust the coefficients to balance the equation

There are two types of numbers that appear in chemical equations. There are subscripts, which are part of the chemical formulas of the reactants and products, and there are coefficients that are placed in front of the formulas to indicate how many molecules of that substance are used or produced. In the chemical formula shown below, the coefficients and subscripts are labeled.



The equation above indicates that one mole of solid copper is reacting with two moles of aqueous silver nitrate to produce one mole of aqueous copper(II) nitrate and two moles of solid silver. Recall that a subscript of 1 is not written - when no subscript appears for an atom in a formula, it is understood that only one atom is present. The same is true in writing coefficients in balanced chemical equations. If only one atom or molecule is present, the coefficient of 1 is omitted.

The subscripts (little numbers) are part of the formulas, and once the formulas for the reactants and products are determined, the subscripts may not be changed. The coefficients (big front numbers) indicate the ratio of each substance involved in the reaction and may be changed in order to balance the equation. Coefficients are inserted into the chemical equation in order to make the total number of each atom on both sides of the equation equal. Note that balancing equations is accomplished by changing coefficients, never by changing subscripts.

Example 1

Balance the following reaction:
Cl_2+NaBr→Br_2+NaCl

By placing a coefficient of 2 in front of NaBr, we can balance the bromine atoms. By placing a coefficient of 2 in front of the NaCl we can balance the chlorine atoms.
Cl_2+ 2 NaBr→Br_2+2 NaCl

A final check shows that we have the same number of each atom on the two sides of the equation. We have also used the smallest whole numbers possible as the coefficients, so this equation is properly balanced.

Example 2

Write a balanced equation for the reaction:
$Al_2(SO_4)_3 + CaBr_2 \rightarrow AlBr_3 + CaSO_4$

In order to balance the aluminum atoms, we must insert a coefficient of 2 in front of the aluminum compound in the products.
$Al_2(SO_4)_3 + CaBr_2 \rightarrow 2AlBr_3 + CaSO_4$

In order to balance the sulfate ions (SO_4^{2-}), we must insert a coefficient of 3 in front of the product $CaSO_4$.

$Al_2(SO_4)_3 + CaBr_2 \rightarrow 2AlBr_3 + 3CaSO_4$

In order to balance the bromine atoms, we must insert a coefficient of 3 in front of the reactant CaBr2.

$Al_2(SO_4)_3 + 3CaBr_2 \rightarrow 2AlBr_3 + 3CaSO_4$

The insertion of the 3 in front of the reactant $CaBr_2$ also balances the calcium atoms in the product $CaSO_4$. A final check shows that there are two aluminum atoms, three sulfur atoms, twelve oxygen atoms, three calcium atoms, and six bromine atoms on each side. This equation is balanced.

Note that this equation would still have the same number of atoms of each type on each side with the following set of coefficients:

$2Al_2(SO_4)_3 + 6CaBr_2 \rightarrow 4AlBr_3 + 6CaSO_4$

Count the number of each type of atom on either side of the equation to confirm that this equation is “balanced”. While this set of coefficients does “balanced” the equation, they are not the lowest set of coefficients possible. Chemical equations should be balanced with the simplest whole number coefficients. We could divide each of the coefficients in this equation by 2 to get another set of coefficients that still balance the equation and are whole numbers. Since it is required that an equation be balanced with the lowest whole number coefficients, the equation above is not properly balanced. When you have finished balancing an equation, you should not only check to make sure it is balanced, you should also check to make sure that it is balanced with the simplest set of whole number coefficients possible.

Summary

- Chemical reactions are represented by chemical equations.
- Chemical equations have reactants on the left, an arrow that symbolizes “yields” or “produces”, and the products on the right.
- Chemical equations are balanced to represent the concept that atoms are neither created nor destroyed.

Putting It Together

Magnesium ribbon burning by Capt. John Yossarian, https://commons.wikimedia.org/wiki/File:Magnesium_ribbon_burning.jpg, CC-BY-SA

Let us revisit this phenomenon:

Remember the burning magnesium? Magnesium oxide is a white solid, has low electrical conductivity, and has high thermal conductivity?

1. What evidence of a chemical change or reaction do you see?
2. Are the properties of magnesium oxide the same as that of magnesium and oxygen? Explain why this is the case.

3.4 Conservation of Matter (Chem.3.4)

Explore this Phenomenon

Image by WikiImages, pixabay.com, CC0

Nuclear bomb testing released carbon-14 which increased the amount found in the atmosphere at that time. This has been seen as an increase in the carbon-14 percent found in organic matter after the nuclear testing compared to organic matter from before the nuclear testing.

1. Why is there a change in the ratio of carbon-14 found in organic matter from before and after nuclear bomb testing?

Standard Chem.3.4

Use mathematics and computational thinking to support the observation that matter is conserved during chemical reactions and matter cycles. Emphasize that chemical reactions occur on both small and global scales, and that matter is always conserved. Examples of small scale reactions could include ratios of reactants and products in a single chemical reaction or simple stoichiometric calculation. Examples of global scale matter cycles could include tracing carbon through the chemical reactions of photosynthesis, combustion, or respiration. (PS1.B)

In this section, pay attention to the amount and types of atoms (matter) before and after chemical reactions. Is the amount and types of atoms (matter) changing? Or staying the same? Is matter created, destroyed, or conserved within systems? Look for evidence in this chapter to support your answer to these questions.

The Law of Conservation of Matter

The law of conservation of mass states that during a chemical reaction the total mass of the products must be equal to the total mass of the reactants. In other words, mass cannot be created or destroyed during a chemical reaction, but must always be conserved.

As an example, consider the reaction between silver nitrate ($AgNO_3$) and sodium chloride (NaCl). These two compounds will dissolve in water to form silver chloride (AgCl) and sodium nitrate ($NaNO_3$). The AgCl does not dissolve in water, so it forms a solid that we can filter off. When we evaporate the water, we can recover the $AgNO_3$ formed. If we react 58.5 grams of NaCl with 169.9 grams of $AgNO_3$, we start with 228.4 grams of materials. After the reaction is complete and the materials separated, we find that we have formed 143.4 grams of AgCl and 85.0 grams of $NaNO_3$, giving us a total mass of 228.4 grams for the products.

$NaCl + AgNO_3 \rightarrow AgCl + NaNO_3$
58.5 g + 169.9 g → 143.4 g + 85.0 g

So, the total mass of the reactants equals the total mass of products, a proof of the law of conservation of mass.

The same idea can be applied to the number of atoms in the $AgNO_3$ and NaCl reaction. The number of each type of atom did not change from the reactants to the products. For example, there are 3 oxygen atoms on both sides of the arrow.

Elements are cycled through the environment over time since the type and number of elements are not going to be created, destroyed, or changed by chemical reactions. This can be seen in the relationship between photosynthesis and respiration. Living organisms release carbon dioxide as a byproduct of cellular respiration which is then removed from the atmosphere by photosynthesis**.**

Interpreting Chemical Equations

Recall that a mole is a quantitative measure equivalent to Avogadro's number of particles ($6.02x10^{23}$). How does the mole relate to the chemical equation? Consider the following reaction:

$$\mathbf{N_2O_3 + H_2O \rightarrow 2HNO_2}$$

We have learned that the coefficients in a chemical equation tell us the relative amounts of each substance involved in the reaction. One way to describe the ratios involved in the reaction above would be, "One molecule of dinitrogen trioxide, N_2O_3, plus one molecule of water yields two molecules of nitrous acid, HNO_3." However, because these are ratios, this statement would be equally valid using units other than molecules. As a result, we could also say, "One dozen dinitrogen trioxide plus one dozen water makes 2 dozen nitrous acid" or "One mole of dinitrogen trioxide plus one mole of water yields two moles of nitrous acid."

We can use moles instead of molecules, because a mole is simply an amount equal to Avogadro's number, just like a dozen is an amount equal to 12. It is important to not use units that describe properties other than amount. For example, it would be incorrect to say that one gram of dinitrogen trioxide plus one gram of water yields two grams of nitrous acid.

Now consider this reaction:

$$\mathbf{2CuSO_4 + 4KI \rightarrow 2CuI + 4K_2SO_4 + I_2}$$

Here, we can say, "Two moles of copper (II) sulfate react with four moles of potassium iodide, yielding two moles of copper(I) iodide, four moles of potassium sulfate, and one mole of molecular iodine." Although we can refer to molecules of iodine, I_2, it is generally not correct to refer to molecules of something like KI. Because KI is an ionic substance that exists as crystal lattices instead of discrete molecules, formula unit is used instead.

Using a Balanced Reaction to Compare Molar Quantities

A mole ratio is the relationship between two components of a chemical reaction. For instance, one way we could read the following reaction is that 2 moles of $H_2(g)$ react with 1 mole of $O_2(g)$to produce 2 moles of $H_2O(l)$:
$2H_2(g)+O_2(g)\rightarrow 2H_2O(l)$

The mole ratio of $H_2(g)$ to $O_2(g)$ would be: $\frac{2 \text{ mole } H_2}{1 \text{ mole } O_2}$

What is the ratio of hydrogen molecules to water molecules? By examining the balanced chemical equation, we can see that the coefficient in front of the hydrogen is 2, while the coefficient in front of water is also 2. Therefore, the mole ratio can be written as:

$$\frac{2 \text{ mole } H_2O}{1 \text{ mole } O_2}$$

Example 1

Find the mole ratios for (1) calcium carbide to water and (2) calcium carbide to calcium hydroxide, given the balanced reaction:
$CaC_2(s) + 2H_2O(l) \rightarrow Ca(OH)_2(aq) + C_2H_2(g)$

Solution:

- Mole ratio of calcium carbide to water

$$\frac{2 \text{ mole } CaC_2}{1 \text{ mole } H_2O} \text{ OR } \frac{1 \text{ mole } H_2O}{2 \text{ mole } CaC_2}$$

- Mole ratio of calcium carbide to calcium hydroxide

$$\frac{2 \text{ mole } CaC_2}{1 \text{ mole } Ca(OH)_2} \text{ OR } \frac{1 \text{ mole } Ca(OH)_2}{2 \text{ mole } CaC_2}$$

The correct mole ratios of reactants and products in a chemical equation are determined by the balanced equation. Therefore, the chemical equation must always be balanced before the mole ratios are used for calculations.

Mole-Mole Calculations

In the chemistry lab, we rarely work with exactly one mole of a chemical. In order to determine the amount of reactant necessary or the amount of product expected for a given reaction, we need to do calculations using mole ratios.

Look at the following equation. If only 0.50 moles of magnesium hydroxide, $Mg(OH)_2$ are present, how many moles of phosphoric acid, H_3PO_4 would be required for the reaction?

$$2H_3PO_4 + 3Mg(OH)_2 \rightarrow Mg_3(PO_4)_2 + 6H_2O$$

Step 1: To determine the conversion factor, we want to convert from moles of $Mg(OH)_2$ to moles of H_3PO_4. Therefore, the conversion factor is:

$$\frac{2 \text{ mole } H_3PO_4}{3 \text{ mole } Mg(OH)_2}$$

Note that what we are trying to calculate is in the numerator, while what we know is in the denominator.

Step 2: Use the conversion factor to answer the question.

$$\frac{0.50 \cancel{\text{mol } Mg(OH)_2}}{} \left| \frac{2 \text{ mol } H_3PO_4}{3 \cancel{\text{mol } Mg(OH)_2}} \right. = 0.33 \text{ mol } H_3PO_4$$

Therefore, if we have 0.50 mol of $Mg(OH)_2$, we would need 0.33 mol of H_3PO_4 to react with all of the magnesium hydroxide. Notice if the equation was not balanced, the amount of H_3PO_4 required would have been calculated incorrectly. The ratio would be 1:1, and we would have concluded that 0.50 mol of H_3PO_4 was required.

Example 2

How many moles of sodium oxide (Na_2O) can be formed from 2.36 mol of sodium nitrate ($NaNO_3$) using the balanced chemical equation below?

$10\ Na + 2\ NaNO_3 \rightarrow 6\ Na_2O + N_2O$

Solution:

$$\frac{2.36 \cancel{\text{mol } NaNO_3}}{} \left| \frac{6 \text{ mol } Na_2O}{2 \cancel{\text{mol } NaNO_3}} \right. = 7.08 \text{ mol } Na_2O$$

Putting It Together

Image by WikiImages, pixabay.com, CC0

Let us revisit this phenomenon:

Nuclear bomb testing released carbon-14 which increased the amount found in the atmosphere at that time. This has been seen as an increase in the carbon-14 percent found in organic matter after the nuclear testing compared to organic matter from before the nuclear testing.

1. How does the law of conservation of matter apply in this situation?

3.5 Conserving Resources (Chem.3.5)

Explore this Phenomenon

Bingham Canyon Mine 1942,CC0
https://en.wikipedia.org/wiki/Kennecott_Utah_Copper#/media/File:Bingham_Canyon_mine_1942.jpg

The Bingham Canyon mine may stop operations in a few decades. There are several factors that could affect the operation of the mine: fluctuations in the prices of minerals like copper, accessibility and availability of the minerals in the mine, landslides like the one in 2014, etc.

1. Pick one factor listed above. List 2-3 ways to reduce this factor's impact on mining operations.

2. What are some possible ways that the mine's operation impacts society?

3. What could be some environmental impacts of the mining and refining of copper?

Standard Chem.3.5

Develop solutions related to the management, conservation, and utilization of mineral resources (matter). *Define the problem, identify criteria and constraints, develop possible solutions using models, analyze data to make improvements from iteratively testing solutions, and optimize a solution.* Emphasize the conservation of matter and minerals as a limited resource. Examples of Utah mineral resources could include copper, uranium, potash, coal, oil, or natural gas. Examples of constraints could include cost, safety, reliability, or possible social, cultural, and environmental impacts. (PS1.B, ESS3.A, ETS1.A, ETS1.B, ETS1.C)

In this section, pay attention to how we obtain, conserve, and use elements and minerals (matter). Are elements and minerals a limited or unlimited resource? How can we use engineering practices to develop and evaluate solutions related to mineral and element use.

What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of stems:

1. Identifying the problem and defining criteria and constraints.
2. Generating ideas for how to solve the problem. Engineers can use research, brainstorming and collaboration with others to come up with ideas for solutions and designs.
3. Build and then test the prototypes. Using data collected, the engineer can analyze how well the various prototypes meet the given criteria and constraints.
4. Evaluate what is needed to improve the leading design or devise a better one.

To design a solution to the problem, you will need to start by identifying the criteria and constraints. Then develop several possible solutions. Once you have several possible solutions, use the criteria and constraints to evaluate each. You should test the solution that will best meet the criteria and constraints, and then determine how to improve the solution, based on test results. Testing the solution may include modeling, working with materials, using mathematical relationships, etc.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

1. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).
2. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Which type of engineering task is utilized in this SEEd Standard?

Mineral Resources

The previous section was on the law of conservation of matter. Recall that it stated that matter cannot be created or destroyed during a chemical reaction. Some minerals are very useful. An ore is a rock that contains minerals with useful elements. Aluminum in bauxite ore (Figure below) is extracted from the ground and refined to be used in aluminum foil and many other products. The cost of creating a product from a mineral depends on how abundant the mineral is and how much the extraction and refining processes cost. Environmental damage from these processes is often not figured into a product’s cost. It is important to use mineral resources wisely.

Aluminum is obtained from the aluminum-bearing minerals in bauxite.
(BauxiteUSGOV.jpg, public domain)

Finding and Mining Minerals

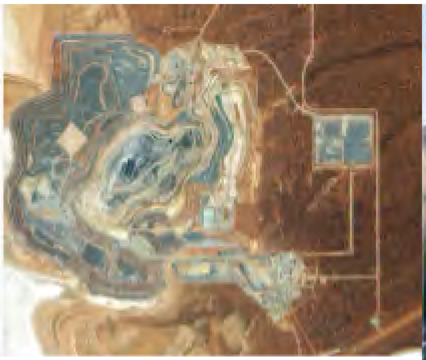
Geologic processes create and concentrate minerals that are valuable natural resources. Geologists study geological formations and then test the physical and chemical properties of soil and rocks to locate possible ores and determine their size and concentration.

A mineral deposit will only be mined if it is profitable. A concentration of minerals is only called an ore deposit if it is profitable to mine. There are many ways to mine ores.

Surface Mining

Surface mining allows extraction of ores that are close to Earth’s surface. Overlying rock is blasted and the rock that contains the valuable minerals is placed in a truck and taken to a refinery. As pictured below, surface mining includes open-pit mining and mountaintop removal. Other methods of surface mining include strip mining, placer mining, and dredging. Strip mining is like open pit mining but with material removed along a strip.

Bingham Canyon Open Pit Copper Mine



An aerial view of an open pit gold mine in Australia

With mountaintop removal, everything lying above an ore deposit is just removed. This controversial mining technique is common in coal mining regions, such as Kentucky (above.)

a) Bingham Canyon copper mine by Loco Steve, https://flic.kr/p/8yFUHC, CC-BY
b) Sunrise Dam Gold Mine, NASA Earth Observatory, public domain
c) Mountaintop Removal Mine above Homes in Eastern Kentucky by iLoveMountains.org, https://flic.kr/p/7ULYSj, CC-BY

These different forms of surface mining are methods of extracting ores close to Earth's surface.

Placers are valuable minerals found in stream gravel. California’s nickname, the Golden State, can be traced back to the discovery of placer deposits of gold in 1848. The gold weathered out of hard metamorphic rock in the western Sierra Nevada, which also contains deposits of copper, lead, zinc, silver, chromite, and other valuable minerals. The gold traveled down rivers and then settled in gravel deposits. Currently, California has active mines for gold and silver and for non-metal minerals such as sand and gravel, which are used for construction.

Underground Mining

Underground mining is used to recover ores that are deeper into Earth’s surface. Miners blast and tunnel into rock to gain access to the ores. How underground mining is approached - from above, below, or sideways - depends on the placement of the ore body, its depth, concentration of ore, and the strength of the surrounding rock.

Underground mining is very expensive and dangerous. Fresh air and lights must also be brought into the tunnels for the miners, and accidents are far too common.

Ore Extraction

The ore’s journey to becoming a usable material is only just beginning when the ore leaves the mine (Figure below). Rocks are crushed so that the valuable minerals can be separated from the waste rock. Then the minerals are separated out of the ore. A few methods for extracting ore are:

- heap leaching: the addition of chemicals, such as cyanide or acid, to remove ore.
- flotation: the addition of a compound that attaches to the valuable mineral and floats.
- smelting: roasting rock, causing it to segregate into layers so the mineral can be extracted.

The de Young Museum in San Francisco is covered in copper panels. Copper is mined and extracted from copper ores.
De Young overlay by Damon Garrett, https://flic.kr/p/3hYxzQ, CC-BY

To extract the metal from the ore, the rock is melted at a temperature greater than 900°C, which requires a lot of energy. Extracting metal from rock is so energy intensive that if you recycle just 40 aluminum cans, you will save the energy equivalent of one gallon of gasoline.

Mining and the Environment

Although mining provides people with many needed resources, the environmental costs can be high. Surface mining clears the landscape of trees and soil, and nearby streams and lakes are inundated with sediment. Pollutants from the mined rock, such as heavy metals, enter the sediment and water system. Acids flow from some mine sites, changing the composition of nearby waterways (Figure below).

Acid drainage from a surface coal mine in Missouri

Iron hydroxide precipitate in stream by USGS Columbia Environmental Research Center, CC0

U.S. law has changed so that in recent decades a mine region must be restored to its natural state, a process called reclamation. This is not true of older mines. Pits may be refilled or reshaped and vegetation planted. Pits may be allowed to fill with water and become lakes or may be turned into landfills. Underground mines may be sealed off or left open as homes for bats.

Summary

- Geologists use many methods to find mineral deposits that will be profitable to mine.
- Ore deposits can be mined by surface or underground mining methods.
- Mining provides important resources but has environmental costs.By U.S. law, currently mined land must undergo reclamation. This is not true for old mines.
- Metal ores must be melted to make metals.
- Minerals are used in a variety of ways.

Review Questions

1. What category of mining would be used to extract ore that is close to the surface? Why?
2. Describe some surface mining methods.
3. What are some disadvantages of underground mining?
4. What are some ways an area can undergo reclamation after being mined?
5. What steps are taken to extract a pure metal from an ore?

Points to Consider

1. Are all mineral deposits ores?
2. Why might an open pit mine be turned into an underground mine?
3. How well does reclaimed land resemble the land before mining began?
4. Under what circumstances might a mineral deposit be an ore one day and not the next?

Putting It Together

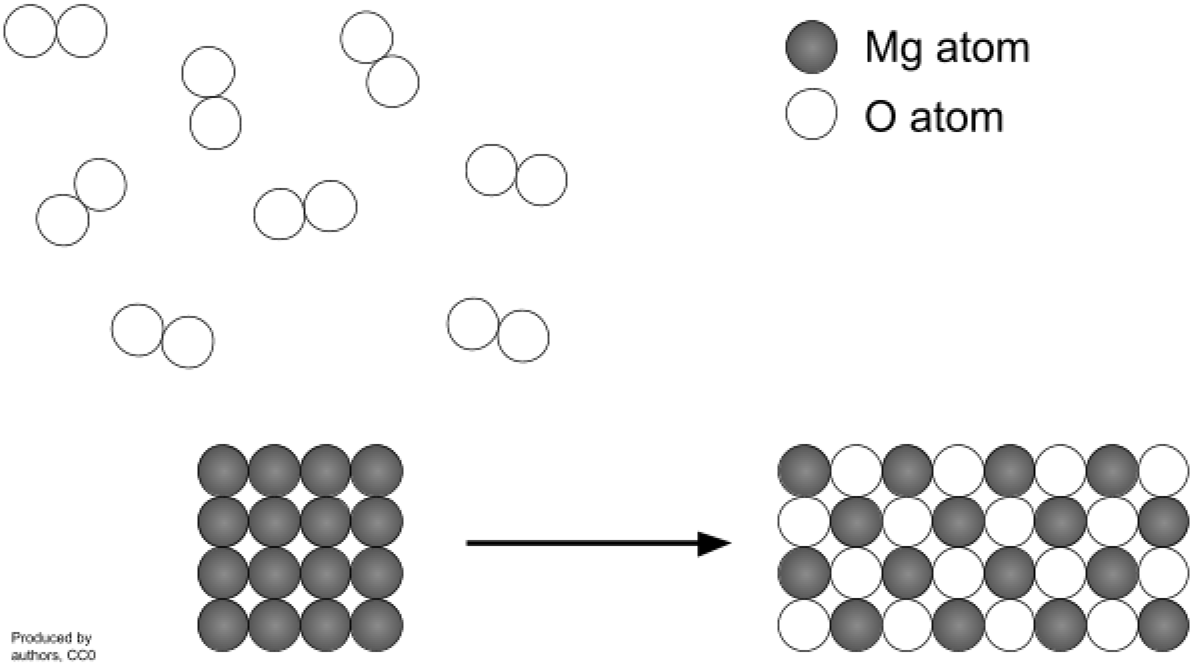
Bingham Canyon Mine 1942,CC0
https://en.wikipedia.org/wiki/Kennecott_Utah_Copper#/media/File:Bingham_Canyon_mine_1942.jpg

The Bingham Canyon mine focuses mainly on obtaining copper. Other natural resources found in Utah are uranium, potash, coal, oil, and natural gas.

1. Pick one of the above natural resources and describe how you would address safety, reliability, environmental impacts, availability of the source, sustainability, and/or cost of obtaining and using the resource.

3.6 Rates of Reactions (Chem.3.6)

Explore this Phenomenon



Produced by authors, CC0

The diagram above is a model of the chemical reaction between magnesium and oxygen. You read about this phenomena in a previous section.

1. Can you explain how the reactants form the products?
2. What could you do to increase the rate at which the products are formed?

Standard Chem.3.6

Construct an explanation using experimental evidence for how reaction conditions affect the rate of change of a reaction. Emphasize collision theory as an explanatory principle. Examples of reaction conditions could include temperature, concentration, particle size, or presence of a catalyst. (PS1.B)

In this section, pay attention to what causes chemical reactions to occur. In particular, what makes collisions between particles effective. How can you change the conditions to affect the rate of change of a reaction?

Collision Theory

Consider the chemical reaction $CH_4+2O_2 \rightarrow CO_2+2H_2O$. In the reactants, the carbon atoms are bonded to hydrogen atoms, and the oxygen atoms are bonded to other oxygen atoms. In order for this reaction to occur, particles must collide in order to break the bonds in the reactants and form the bonds within the products.

The collision theory – (a model that explains that reactants must collide in order to react) explains why reactions occur between particles. The collision theory provides us with the ability to predict what conditions are necessary for a successful reaction to take place. These conditions include:

- The particles must collide with each other.
- The particles must have proper orientation.
- The particles must collide with sufficient energy to break the old bonds.

The rate of the reaction depends on the fraction of molecules that have enough energy and that collide with the proper orientation.

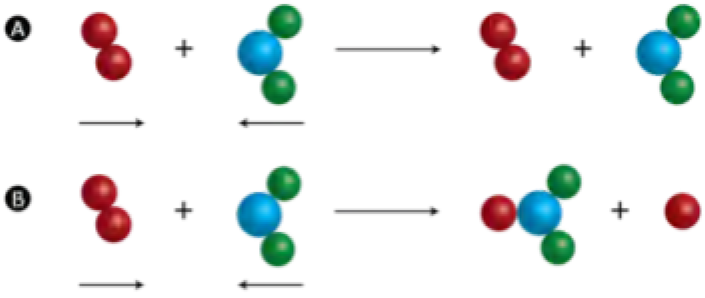


Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC-SA 3.0

In those cases where the reactants do not collide with enough energy to break the old bonds, the reactant particles will simply bounce off each other and remain reactant particles.

The bonds in the products cannot form unless the bonds in the reactants are first broken, which requires an input of energy called activation energy. The energy to break the old bonds comes from the kinetic energy of the reactant particles. The reactant particles are moving around at random with an average kinetic energy related to the temperature. If a reaction is to occur, the kinetic energy of the reactants must be high enough that when the reactant particles collide, the collision is forceful enough to break the old bonds. Once the old bonds are broken, the atoms in the reactants would be available to form new bonds. At that point, the new bonds of the products could be formed. When the new bonds are formed, potential energy (stored energy) is released.

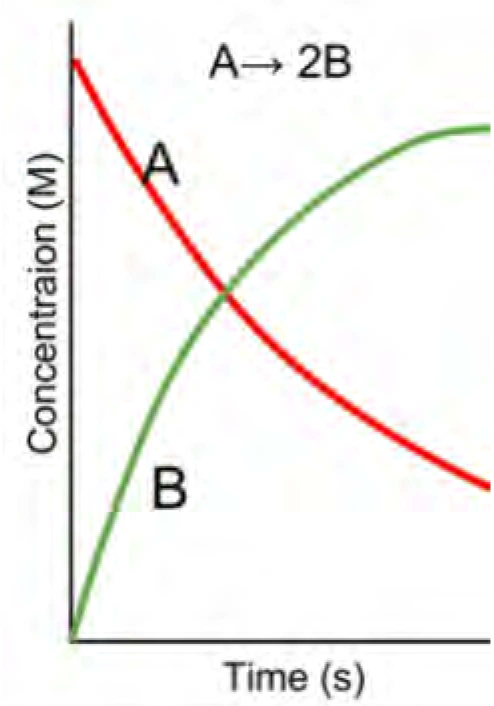
What is chemical reaction rate?

Large Sodium Explosion, CC0

Sodium reacts violently with water. That's what is happening in the picture. Why does sodium have such explosive reactions? It's because the reactions occur so quickly.

How fast a chemical reaction occurs is called the reaction rate (a measure of how fast products are made in a chemical reaction). The rate of a reaction can be obtained by graphing how the concentration of a reactant or product changes over time. The slope of the line is the rate of the reaction. A steeper slope, means the reaction is going faster. Consider the following example.

In this reaction, the reactant (A) is being used to make the product, and its concentration is going down as it is being used. The concentration of the product (B) is going up, as more and more of it is made over time.



Tracy Poulsen, CC-BY

Several factors affect the rate of a given chemical reaction. They include the following:

- Temperature of reactants
- Concentration of reactants
- Surface area of reactants
- Presence of a catalyst

Temperature of Reactants

When the temperature of reactants increases, the rate of the reaction increases. At higher temperatures, particles of reactants have more energy, so they move faster. As a result, they are more likely to bump into one another and collide with greater force. For example, food spoils because of chemical reactions, and these reactions occur faster at higher temperatures (see the bread on the left in the Figure). This is why we store food in the refrigerator or freezer (like the bread on the right below in the Figure). The lower temperature slows the rate of spoilage.

Bread after 1 month on warm countertop

Moldy Bread by Ciar, CC0

Bread after 1 month in cold fridge

Bread Loaf by Jeff Keacher, https://flic.kr/p/4cVKJF, CC-BY

There are two major effects due to increasing the temperature: more frequent collisions, and more energetic collisions. Thus, more particles will collide, and more of those collisions will have enough energy for a reaction to occur. In other words, more particles will have the energy needed in order to react.

Concentration of Reactants

The rate of a reaction also depends on concentration (the number of particles of a substance in a given volume). When the concentration of reactants is higher, the reaction rate is faster. At higher concentrations, particles of reactants are crowded closer together, so they are more likely to collide and react. Did you ever see a sign like the one in the figure? You might see it where someone is using a tank of pure oxygen for a breathing problem. Combustion, or burning, is a chemical reaction in which oxygen is a reactant. A greater concentration of oxygen in the air makes combustion more rapid if a fire starts burning.

Image by Christopher Auyeung, CK-12 Foundation, CC-BY-NC 3.0

If you had one red ball and one green ball flying around randomly in an enclosed space and undergoing collisions with the walls and with each other, in a given amount of time the balls would collide with each other a certain number of times as determined by probability. If you now put two red balls and one green ball in the room under the same conditions, the probability of a collision between a red ball and the green ball would exactly double. The green ball would have twice the chance of encountering a red ball in the same amount of time.

The rate of reaction is proportional to the number of collisions in a certain amount of time, so increasing the concentration of either reactant increases the number of collisions, the number of successful collisions, and the reaction rate.

Surface Area of Reactants

When a solid substance is involved in a chemical reaction, only the matter at the surface of the solid is exposed to other reactants. If a solid has more surface area, more of it is exposed and able to react. Therefore, increasing the surface area of solid reactants increases the reaction rate. Look at the hammer and nails pictured in the Figure. Both are made of iron and will rust when iron combines with oxygen in the air. However, the nails have a greater surface area, so they will rust faster.

Hammer by Frank Boston, https://flic.kr/p/5SJBvA, CC-BY
Nails by internets_dairy, https://flic.kr/p/6wmdAA, CC-BY

Summary

- With increasing temperature, the kinetic energy of the particles and the number of particles with energy greater than the activation energy increases.
- How fast a chemical reaction occurs is called the reaction rate.
- Several factors affect the rate of a chemical reaction, including the temperature, concentration, and surface area of reactants, and the presence of a catalyst.

Online Interactive Activities

- See how changing the concentration affects reaction rate by using this online tool: http://go.uen.org/b7B
- Change the temperature and watch how the reaction rate changing in this online lab: http://go.uen.org/b7E

Think like a Chemist

Watch the video about the reaction rate at the following URL, and then answer the questions below.

- https://go.uen.org/b7F

1. What is collision theory?

2. How does collision theory relate to factors that affect reaction rate?

3. Explain why chemical reactions are able to occur at room temperature even though very few collisions are successful.

4. What would happen in a collision between two particles if there was insufficient kinetic energy and improper geometric orientation?

   a. The particles would rebound and there would be no reaction.
   b. The particles would keep bouncing off each other until they eventually react, therefore the rate would be slow.
   c. The particles would still collide but the by-products would form.
   d. The temperature of the reaction vessel would increase.

5. Define reaction rate.

6. What is activation energy?

7. Why do reactants need energy in order for a chemical reaction to begin?

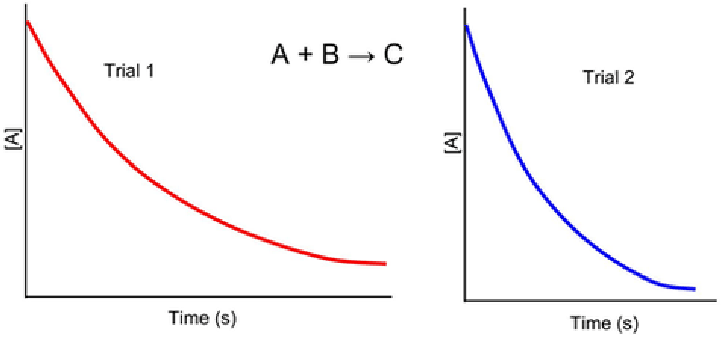
$NaHCO_3(s)+HC_2H_3O_2(aq) \rightarrow H_2O(l)+CO_2(g)+NaC_2H_3O_2(aq)$

8. What would be the effect of each of the following changes on the reaction rate?

   a. Powdered baking soda is used instead of a big chunk.
   b. The concentration of vinegar (HC2H3O2) is decreased to half its original concentration.
   c. The vinegar is heated before the reaction.
   d. Explain what is wrong with the following statement: Food spoils faster at higher temperatures because heat is a catalyst.

9. Which trial has the faster reaction rate? Why?

10. What condition(s) could be changed to cause the change in reaction rate from Trial 1 to Trial 2?



Catalysts

What is a catalyst? Chemical reactions require a certain amount of energy just to get started. This energy is called activation energy. For example, activation energy is needed to start a car engine. Turning the key causes a spark that activates the burning of gasoline in the engine. The combustion of gas won't occur without the spark of energy to begin the reaction.

Q: Why is activation energy needed? Why won't a reaction occur without it?

A: A reaction won't occur unless atoms or molecules of reactants come together. This happens only if the particles are moving, and movement takes energy. Often, reactants have to overcome forces that push them apart. This takes energy as well. Still more energy is needed to start breaking bonds in reactants.

The addition of a catalyst (a substance that increases the rate of a chemical reaction without being used up) is another way to speed up a reaction. Catalysts lower the activation energy for a reaction. A catalyst isn't a reactant in a chemical reaction, but it speeds the reaction up. As a result, it isn't changed or used up in the reaction, so it can go on to catalyze many more reactions.

The tunnel through this mountain provides a faster route for cars to get to the other side of the mountain. If a chemical reaction were like a road to the other side of a mountain, a catalyst would be like a tunnel.

Image by Bishnu Sarangi , pixabay.com, CC0

Q: How is a catalyst like a tunnel through a mountain?

A: Like a tunnel through a mountain, a catalyst provides a faster pathway for a chemical reaction to occur.

Catalysts interact with reactants so the reaction can occur by a different pathway that has a lower activation energy. Activation energy is the energy needed to start a reaction. When activation energy is lower, more reactant particles have enough energy to react so the reaction goes faster. Many catalysts work like the one in the diagram below. The catalyst brings the reactants together by temporarily bonding with them. This makes it easier and quicker for the reactants to react together. The catalyst is released by the product molecule at the end of the reaction.

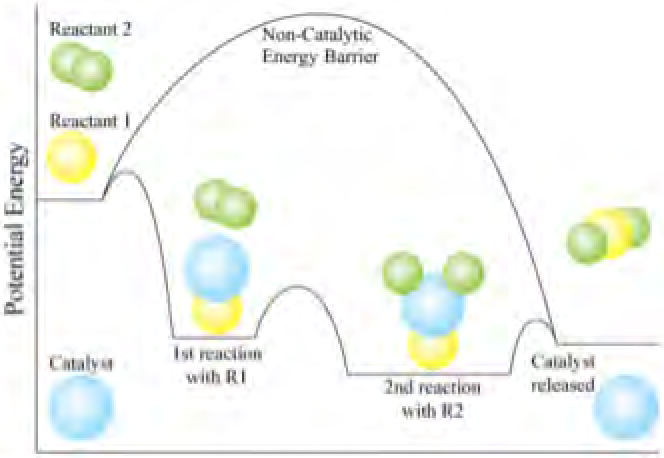


Image by Zachary Wilson, CK-12 Foundation, CC-BY-NC 3.0

Q: In this diagram, look at the energy needed in the catalytic and noncatalytic pathways of the reaction. How does the amount of energy compare? How does this affect the reaction rate along each pathway?

A: The catalytic pathway of the reaction requires far less energy. Therefore, the reaction will occur faster by this pathway because more reactants will have enough energy to react.

Catalysts in Living Things

Chemical reactions constantly occur inside living things. Many of these reactions require catalysts so they will occur quickly enough to support life. Catalysts in living things are called enzymes. Enzymes can be extremely effective. A reaction that takes a split second to occur with an enzyme might take many years without it!

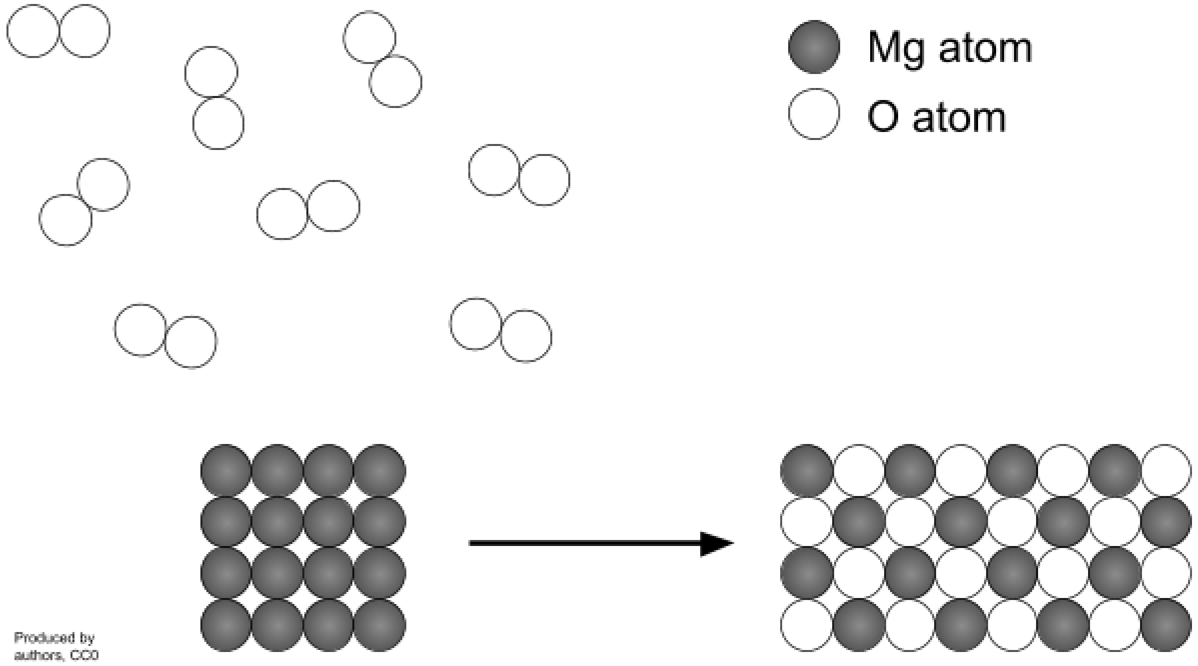
More than 1000 different enzymes are necessary for human life. Many enzymes are needed for the digestion of food. An example is amylase, which is found in the mouth and small intestine. Amylase catalyzes the breakdown of starch to sugar. You can see how it affects the rate of starch digestion in the graph below.

Q: If you chew a starchy food such as a soda cracker for a couple of minutes, you may notice that it starts to taste slightly sweet. Why does this happen?
A: The starches in the cracker start to break down to sugars with the help of the enzyme amylase. Try this yourself and see if you can taste the reaction.

Summary

- A catalyst is a substance that increases the rate of a chemical reaction. A catalyst provides an alternative pathway for the reaction that has a lower activation energy. When activation energy is lower, more reactant particles have enough energy to react, so the reaction occurs faster.
- Chemical reactions constantly occur inside living things, and many of them require catalysts to occur quickly enough to support life. Catalysts in living things are called enzymes.

Putting It Together



Produced by authors, CC0

Let us revisit this phenomenon:

The diagram above is a model of the chemical reaction between magnesium and oxygen.

1. How does collision theory apply in the above diagram?
2. What will happen to the rate of reaction if the magnesium is broken into 4 pieces instead of 1? Explain why that change occurs.
3. What will happen to the rate of reaction if the concentration of magnesium and oxygen are cut in half? Explain why that change occurs.

3.7 Equilibrium (Chem.3.7)

Explore this Phenomenon

tea-pot-hard-water-stain by .fairydust., https://flic.kr/p/zWCQrC, CC-BY-NC-ND

Hard water is formed when ions in water precipitate. A typical reaction is:
$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftarrows CaCO_3(s)$ $\Delta H=13.1$ kJ/mol

The hard water spots are solid carbonate that form. When too much hard water builds up, it can reduce the flow of water in pipes, affect the effectiveness of dishwashers and water heaters, as well as leave unsightly messes on dishes.

1. List some ways in which you can reduce the formation of hard water spots or remove them by shifting the equilibrium.

2. Use a cause and effect relationships and collision theory to explain why your mechanism might work.

Standard Chem.3.7

Design a solution that would refine a chemical system by specifying a change in conditions that would produce increased or decreased amounts of a product at equilibrium. *Define the problem, identify criteria and constraints, develop possible solutions using mod*els, *analyze data to make improvements from iteratively testing solutions, and optimize a solution*. Emphasize a qualitative understanding of Le Châtelier's Principle and connections between macroscopic and molecular level changes. (PS1.B, ETS1.A, ETS1.B, ETS1.C)

In this section, pay attention to change in natural and man made systems. In particular, think about what conditions will favor forward or reverse chemical reactions. How will changing the conditions affect the outcome of chemical reactions.

What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of stems:

5. Identifying the problem and defining criteria and constraints.
6. Generating ideas for how to solve the problem. Engineers can use research, brainstorming and collaboration with others to come up with ideas for solutions and designs.
7. Build and then test the prototypes. Using data collected, the engineer can analyze how well the various prototypes meet the given criteria and constraints.
8. Evaluate what is needed to improve the leading design or devise a better one.

To design a solution to the problem, you will need to start by identifying the criteria and constraints. Then develop several possible solutions. Once you have several possible solutions, use the criteria and constraints to evaluate each. You should test the solution that will best meet the criteria and constraints, and then determine how to improve the solution, based on test results. Testing the solution may include modeling, working with materials, using mathematical relationships, etc.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

3. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria

and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).

4. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Which type of engineering task is utilized in this SEEd Standard?

Products

Remember from chapter 3.3 you learned about balanced chemical reactions.

$A + B \rightarrow AB$

Remember also that matter is always conserved, meaning that however many atoms of reactant A is used there must be the same number of atoms of A in the products. This is also true for the atoms that make up reactant B.

As another example, if

$2A + B_2 \rightarrow 2AB$

then there are 2 moles of A in the reactant, 1 mole of B_2 in the reactants, yielding 2 moles of AB in the products. The reactants have broken certain bonds during the reaction and formed new ones in the products.

To understand what happens microscopically we use the chemical reaction of water.

$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (l)$

Microscopically 2 molecules of H_2, hydrogen, gas is reacting with 1 molecule of O_2, oxygen, gas produces 2 molecules of liquid water. However, in chemistry it is very inefficient to do this reaction because it is very difficult to measure 2 molecules of hydrogen gas and only 2 molecules.

The chemistry unit of a mole allows us to change this microscopic problem to a macroscopic one. It allows us to now say that we need 2 moles of H_2, hydrogen, gas is reacting with 1 mole of O_2, oxygen, gas produces 2 moles of liquid water. If you use the correct amounts of each reactant then you should be able to yield the full amount of product. If you use more of the amount shown in the balanced chemical formula then you will get more product. This means that if you start with less reactant you will yield less product.

Introduction to Equilibrium

Consider this generic reaction: A+B→C+D. Based on what we have learned so far, you might assume that the reaction will keep going forward, forming C and D until either A or B (or both) is completely used up. When this is the case, we would say that the reaction "goes to completion". Reactions that go to completion are referred to as irreversible reactions – (reactions where products cannot be converted back into reactants).

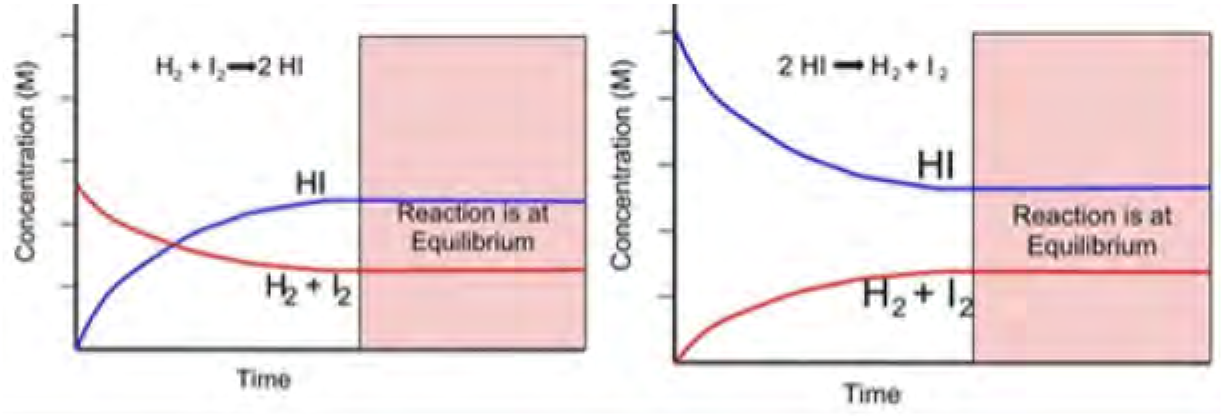
Some reactions, however, are reversible reactions (reactions where products can also react to re-form the reactants). In our example, this would correspond to the reaction C+D→A+B. During a reversible reaction, both the forward and backward reactions are happening at the same time.

Equilibrium

As we learned earlier, the rate of a reaction depends on the concentration of the reactants. At the very beginning of the reaction A+B→C+D, we would not expect the reverse reaction to proceed very quickly. If only a few particles of C and D have been created in a large flask of A and B, then it is very unlikely that they will find each other because the concentration of C and D is just too low. If C and D cannot "find" each other and collide with the correct energy and orientation, no reaction will occur.

However, as more and more C and D are created, it becomes more and more likely that they will find each other and react to re-form A and B. Conversely, as A and B are being used up, the forward reaction slows down for the same exact reason. The concentration of A and B decreases over the course of a reaction because there are fewer A and B particles in the same size flask. At some point, the rates for the forward and reverse reactions will be equal, at which point the concentrations will no longer change. If A and B are being destroyed at the same rate that they are being created, the overall amount should not change over time. At this point, the system is said to be in equilibrium – (when the rate of the forward reaction is equal to the rate of the reverse reaction). A qualitative description of this process for the reaction between hydrogen and iodine to make hydrogen iodide is shown below.

Chemists use a double arrow to show that a reaction is in equilibrium. For the reaction above, the chemical equation would be:



$$H_2 + I_2 \rightleftharpoons 2HI$$

Tracy Poulsen, CC-BY

This indicates that both directions of the reaction are occurring. Note that a double-headed arrow (↔) should not be used here because this has a different chemical meaning.

Changes to Equilibrium Systems

When a reaction has reached equilibrium with a given set of conditions, if the conditions are not changed, the reaction will remain at equilibrium forever. The forward and reverse reactions continue at the same equal and opposite rates.

It is possible, however, to alter the reaction conditions. For example, you could increase the concentration of one of the products, or decrease the concentration of one of the reactants, or change the temperature. When a change of this type is made in a reaction at equilibrium, the reaction is no longer in equilibrium. When you alter something in a reaction at equilibrium, chemists say that you put stress on the equilibrium. When this occurs, the reaction will no longer be in equilibrium, so the reaction itself will begin changing the concentrations of reactants and products until the reaction comes to a new position of equilibrium. How a reaction will change when a stress is applied can be explained and predicted and is the topic of this lesson.

Le Châtelier’s Principle

In the late 1800s, a chemist by the name of Henry-Louis Le Châtelier was studying stresses that were applied to chemical equilibria. He formulated a principle, Le Châtelier’s Principle, which states that when a stress is applied to a system at equilibrium, the equilibrium will shift in a direction to partially counteract the stress and once again reach equilibrium. For instance, if a stress is applied by increasing the concentration of a reactant, the equilibrium position will shift toward the right and remove that stress by using up some of the reactants. The reverse is also true. If a stress is applied by lowering a reactant concentration, the equilibrium position will shift toward the left, this time producing more reactants to partially counteract that stress.

The same reasoning can be applied when some of the products are increased or decreased.

Effect of Concentration Changes

Let's use Le Châtelier's principle to explain the effect of concentration changes on an equilibrium system. Consider the generic equation:

$aA(aq) + bB(aq) \rightleftharpoons cC(aq) + dD(aq)$

At equilibrium, the forward and reverse rates are equal. The concentrations of all reactants and products remain constant, which keeps the rates constant. Suppose we add some additional A, thus raising the concentration of A without changing anything else in the system. Since the concentration of A is larger than it was before, the forward reaction rate will suddenly be higher. The forward rate will now exceed the reverse rate. Now there is a net movement of material from the reactants to the products. As the reaction uses up reactants, the forward rate that was too high slowly decreases while the reverse rate that was too low slowly increases. The two rates are moving toward each other and will eventually become equal again. They do not return to their previous rates, but they do become equal at some other value. As a result, the system returns to equilibrium.

Le Châtelier's principle says that when you apply a stress (adding A), the equilibrium system will shift to partially counteract the applied stress. In this case, the reaction shifts toward the products so that A and B are used up and C and D are produced. This reduction of the concentration of A is counteracting the stress you applied (adding A).

Suppose instead that you removed some A instead of adding some. In that case, the concentration of A would decrease, and the forward rate would slow down. Once again, the two rates are no longer equal. At the instant you remove A, the forward rate decreases, but the reverse rate remains exactly what it was. The reverse rate is now greater than the forward rate, and the equilibrium will shift toward the reactants. As the reaction runs backward, the concentrations of C and D decrease slowing the reverse rate, and the concentrations of A and B increase, raising the forward rate. The rates are again moving toward each other, and the system will again reach equilibrium. The shift of material from products to reactants increases the concentration of A, thus counteracting the stress you applied. Le Châtelier's principle again correctly predicts the equilibrium shift.

The effect of concentration on the equilibrium system according to Le Châtelier is as follows: increasing the concentration of a reactant causes the equilibrium to shift to the right, using up reactants and producing more products. Increasing the concentration of a product causes the equilibrium to shift to the left, using up products and producing more reactants. The same reasoning can be applied to products that are removed from the system.

Example 1

For the reaction, what would be the effect on the equilibrium system if:
$SiCl_4(g) + O_2(g) \rightleftharpoons SiO_2(s) + 2Cl_2(g)$

- $SiCl_4$ increases
- O_2 increases
- Cl_2 increases

Solution:

- The equilibrium would shift to the right. Cl_2 would increase, more SiO_2 would be produced, and O_2 would decrease.
- The equilibrium would shift to the right. $SiCl_4$ would decrease, more SiO_2 would be produced, and Cl_2 would increase.
- The equilibrium would shift left. $SiCl_4$ and O_2 would increase, and SiO_2 would be used up.

Let's take a moment to consider what happens to the concentration of a reactant or product that is changed. In our theoretical reaction, if you add A, the concentration of A will increase. The equilibrium shifts toward the products, and A is used. Where does the concentration of A end up, higher or lower than the original concentration? The concentration of A increases when you add more A, but it decreases as the equilibrium shifts. A new equilibrium, however, will be reached before the concentration of A gets back down to its original concentration.

This is why Le Châtelier's principle says the equilibrium will shift to partially counteract the applied stress. The equilibrium shift will move toward returning the concentration to where it was before you applied stress, but the concentration never quite gets back to the original value before a new equilibrium is established.

Example 2

For the reaction $PCl_3(g)+Cl_2(g)\rightleftharpoons PCl_5(g)$, which way will the equilibrium shift if:

- PCl_3 decreases
- Cl_2 decreases
- PCl_5 decreases

Solution:

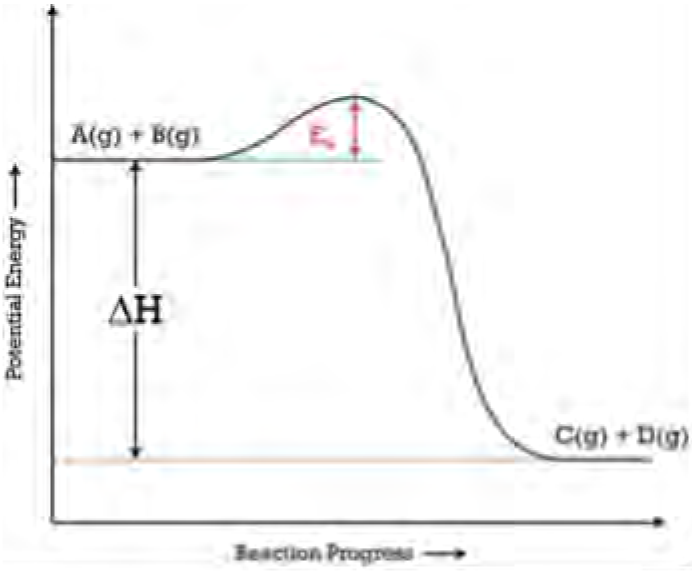
- left
- left
- right

Effect of Changing Temperature

In the previous section, you learned that one of the most important factors that determines reaction rate is temperature. Raising the temperature will increase the average speed of the individual particles, thus causing more frequent collisions. Additionally, this increase in energy means that more particles will have the energy necessary to overcome the activation barrier. Overall, a rise in temperature increases both the frequency of collisions and the percentage of successful collisions.

It should be clear that increasing the temperature of the reaction vessel will increase both the forward and reverse reaction rates, but will it increase both rates equally? Let's examine the potential energy diagram of a reaction to see if we can gain any insight there. Here is the potential energy diagram for our usual theoretical reaction:

$A(g)+B(g)\rightarrow C(g)+D(g)$



CK-12 Foundation, CC-BY-NC-SA 3.0

As you can see, the forward reaction has a small energy barrier while the reverse reaction has a very large energy barrier. With the reactants and products at the same temperature, the forward reaction will be much faster than the reverse reaction if the concentration of reactants is equal to the concentration of products.

Suppose we were to increase the temperature of the reaction system by 10 degrees C. Both the forward and reverse reaction rates will increase because a higher percentage of reactants and products will have enough energy to overcome the activation barrier. However, the reverse reaction rate will be more drastically affected. The activation barrier for the reverse reaction is so large that very few molecules would be able to overcome the barrier at the lower temperature. When the temperature is raised, there is a significant increase in the number of product molecules that can overcome the activation barrier. On the other hand, the activation barrier for the forward reaction is so small that many of the molecules would be able to overcome the barrier at the lower temperature. When the temperature is raised, there is only a small increase in the number of reactant molecules that can overcome the activation barrier. Thus, the rate of the reverse reaction will increase more dramatically than the rate of the forward reaction. The equilibrium will shift to the left, producing more reactants until a new equilibrium is established.

All reactions are either endothermic or exothermic, so there will always be a difference in the activation energy for the forward and reverse reactions. Whenever the temperature is raised, it will add energy to the system and increase both the forward and reverse reaction rates. However, it will more significantly increase the rate of the slower reaction. In an exothermic reaction, the reverse reaction has a higher activation barrier, and is thus slower. When heat is added, the reverse reaction will speed up more than the forward reaction, and the equilibrium will shift to the left. In an endothermic reaction, the forward reaction has a higher activation barrier, and is thus slower. When heat is added, the forward reaction will speed up more than the reverse reaction, and the equilibrium will shift to the right. By looking at a potential energy diagram, you should be able to tell 1) whether the reaction is exothermic or endothermic, 2) whether the forward or reverse reaction would be slower, assuming equal concentrations of reactants and products, and 3) which direction the equilibrium would shift in response to a change in temperature.

Following the same reasoning as above, we can see that decreasing the temperature of a reaction produces an equilibrium shift in the opposite direction. Cooling an exothermic reaction results in a shift to the right, and cooling an endothermic reaction causes a shift to the left. Le Châtelier's principle correctly predicts the equilibrium shift when systems are heated or cooled. An increase in temperature is the same as adding energy to the system. Look at the following reaction:

$$\mathbf{2SO_2(g)+O_2(g)\rightleftharpoons 2SO_3(g)\ \Delta H=-191\ kJ}$$

This could also be written as:

2SO2(g)+O2(g)⇌2SO3(g)+191 kJ

When changing the temperature of a system at equilibrium, energy can be thought of as just another product or reactant. For this reaction, 191 kJ of energy is produced for every mole of O_2 and 2 moles of SO_2 that react. Therefore, when the temperature of this system is raised, the effect will be the same as increasing any other product. As the temperature is increased, the equilibrium will shift away from the stress, resulting in more reactants and less products. As you would expect, the reverse would be true if the temperature is decreased. A summary of the effect temperature has on equilibrium systems is shown in the next table:

	Exothermic (−ΔH)	Endothermic (+ΔH)
Increase Temperature	Shifts left, favors reactants	Shifts right, favors products
Decrease Temperature	Shifts right, favors products	Shifts left, favors reactants

Example 3

Predict the effect on the equilibrium position if the temperature is increased in each of the following:

- $H_2(g)+CO_2(g)\rightleftharpoons CO(g)+H_2O(g)\Delta H=+40\text{ kJ}$
- $2SO_2(g)+O_2(g)\rightleftharpoons SO_3(g)+\text{energy}$

Solution:

- The reaction is endothermic. With an increase in temperature for an endothermic reaction, the reaction will shift right, producing more products.
- The reaction is exothermic. With an increase in temperature for an exothermic reaction, the reaction will shift left, producing more reactants.

The Haber Process

The reaction between nitrogen gas and hydrogen gas can produce ammonia, NH_3.However, under normal conditions, this reaction does not produce very much ammonia. Early in the 20th century, the commercial use of this reaction was too expensive because of the low yield.

$N_2(g)+3\mathbf{H_2(g)\rightleftharpoons 2NH_3(g)+energy}$

A German chemist named Fritz Haber applied Le Châtelier’s principle to help solve this problem. Decreasing the concentration of ammonia by immediately removing it from the reaction container causes the equilibrium to shift to the right, so the reaction can continue to produce more products.

One more factor that will affect this equilibrium system is the temperature. Since the forward reaction is exothermic, lowering the temperature will once again shift the equilibrium system to the right and increase the ammonia produced. Unfortunately, this process also has a very high activation energy, so if the temperature is too low, the reaction will slow to a crawl. Thus, a balance must be struck between shifting the equilibrium to favor products and allowing products to be formed at a reasonable rate. It was found that the optimum conditions for this process (the ones that produce the most ammonia the fastest) are 550°C and 250 atm of pressure, with the ammonia being continually removed from the system.

Summary

- Irreversible reactions will continue to form products until the reactants are fully consumed.
- Reversible reactions will react until a state of equilibrium is reached.
- Dynamic equilibrium refers to an equilibrium where forward and reverse reactions are still occurring, but they are proceeding at the same rate, so there is no net change.
- In a dynamic equilibrium the concentrations of the reactants and products are constant.
- Increasing the concentration of a reactant causes the equilibrium to shift to the right, producing more products.
- Increasing the concentration of a product causes the equilibrium to shift to the left, producing more reactants.
- Decreasing the concentration of a reactant causes the equilibrium to shift to the left, using up some products.
- Decreasing the concentration of a product causes the equilibrium to shift to the right, using up some reactants.

Changing the temperature of a reaction system will cause a shift in equilibrium based on the ΔH of the reaction. Heating an endothermic reaction causes a shift toward the products. Heating an exothermic reaction causes a shift toward the reactants.

Putting It Together

tea-pot-hard-water-stain by .fairydust., https://flic.kr/p/zWCQrC, CC-BY-NC-ND

Hard water is formed when ions in water precipitate. A typical reaction is:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftarrows CaCO_3(s)$$

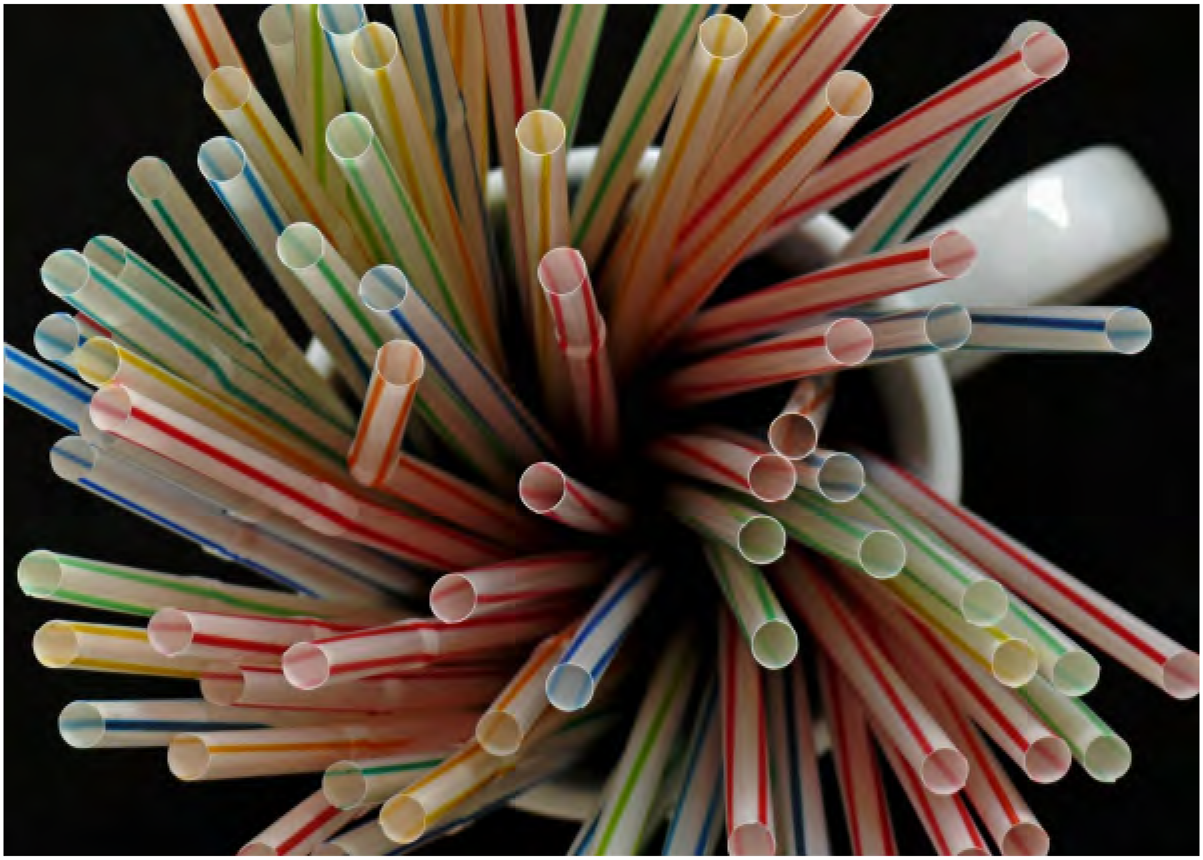
The hard water spots are solid carbonate that form. When too much hard water builds up, it can reduce the flow of water in pipes, affect the effectiveness of dishwashers and water heaters, as well as leave unsightly messes on dishes.

1. List some ways in which you can reduce the formation of hard water spots or remove them by shifting the equilibrium.

2. Use a cause and effect relationships and collision theory to explain why your mechanism might work.

3.8 Designed Chemicals (Chem.3.8)

Explore this Phenomenon



http://www.peakpx.com/411589/stripe-drinking-straw-lot, CC0

Some states have banned plastic straws.

1. Why do you think straws were banned in some states?
2. Do you agree with the ban? Why or why not.

In this section, you will evaluate the effects of designed chemicals like plastic in complex real-world systems.

Standard Chem.3.8

Obtain, evaluate, and communicate information regarding the effects of designed chemicals in a complex real-world system. Emphasize the role of chemistry in solving problems, while acknowledging unintended consequences. Examples could include ozone depletion and restoration, DDT, development of medicines, the preservation of historical artifacts, or use of bisphenol-A in plastic manufacturing. (PS1.A)

In this section, pay attention to the effects of man-made chemicals in complex systems. In particular, notice how designed compounds solve problems but also could have unintended consequences.

Designer Chemicals

Plastics are extremely versatile and have been used to make life better, healthier, and safer. Plastics are used in airbags, child car seats, and bike helmets. They are used in televisions, phones, and other electronic equipment. Plastics in packaging keep food safe and fresh.

Plastics have been made in a variety of structures and functions. Rubber is an example of a natural plastic. Some plastics are hard and shatter-resistant; others are soft and flexible.

How could these straws affect a sea turtle?

Plastic pollution is growing at an alarming rate. Our oceans are becoming more and more polluted and sea turtles are suffering. The production of plastic straws in the United States is contributing to a global epidemic that is killing off our already endangered sea turtles. Sea turtles can ingest the straws whole or broken up into smaller pieces and the straws can also become lodged in their bodies.

The United States uses approximately 500 million plastic straws every day. While straws may not be the top contender for volume in the vast plastic garbage mass that floats in the ocean, they are some of the more dangerous ones. Straws can be ingested whole, wind up entangled or even find themselves lodged in the noses of sea turtles. The longer straws have been floating in the ocean, the more they break down into tiny micro pieces that are then swallowed. These micro pieces of plastic fill up the stomach without providing any form of nutrients and often times leech harmful chemicals in the animal’s stomach.

Marine Trash

Trash from land may end up as trash in the ocean, sometimes extremely far from land. Some of it will eventually wash ashore, possibly far from where it originated (Figure below).

Image by H. Hach, pixabay.com, CC0

Sources of Trash

Although people had once thought that the trash found everywhere at sea was from ships, it turns out that 80% is from land. Some of that is from runoff, some is blown from nearshore landfills, and some is dumped directly into the sea.

The 20% that comes from ships at sea includes trash thrown overboard by large cruise ships and many other vessels. It also includes lines and nets from fishing vessels. Ghost nets, nets abandoned by fishermen intentionally or not, float the seas and entangle animals so that they cannot escape. Containers sometimes go overboard in storms. Some noteworthy events, like a container of rubber ducks that entered the sea in 1992, are used to better understand ocean currents. The ducks went everywhere!

Makeup of Trash

About 80% of the trash that ends up in the oceans is plastic. This is because a large amount of the trash produced since World War II is plastic. Also many types of plastic do not biodegrade, so they simply accumulate. While many types of plastic photodegrade — that is, they break up in sunlight — this process only works when the plastics are dry. Plastic trash in the water does break down into smaller pieces, eventually becoming molecule-sized polymers. Other trash in the oceans includes chemical sludge and materials that do biodegrade, like wood.

Toxic chemicals

Some plastics contain toxic chemicals, such as bisphenol A. Plastics can also absorb organic pollutants that may be floating in the water, such as the pesticide DDT (which is banned in the U.S. but not in other nations) and some endocrine disruptors.

Effect on Organisms

Marine birds such as albatross, or animals like sea turtles, live most of their lives at sea and just come ashore to mate. These organisms can’t break down the plastic and they may eventually die (Figure below). Boats may be affected. Plastic waste is estimated to kill 100,000 sea turtles and marine mammals annually, but exact numbers are unknown.

Albatross chick plastic, USFWS, public domain

This albatross likely died from the plastic it had ingested.

Plastic shopping bags are extremely abundant in the oceans. If an organism accidentally ingests one, it may clog digestion and cause starvation by stopping food from moving through or making the animal not feel hungry.

The Great Pacific Garbage Patch

Trash from the lands all around the North Pacific is caught up in currents. The currents bring the trash into the center of the North Pacific Gyre. Scientists estimate that it takes about six years for trash to move from the west coast of North America to the center of the gyre. The concentration of trash increases toward the center of the gyre.

While recognizable pieces of garbage are visible, much of the trash is tiny plastic polymers that are invisible but can be detected in water samples. The particles are at or just below the surface within the gyre. Plastic confetti-like pieces are visible beneath the surface at the gyre's center.

canal debris by Andrew, https://flic.kr/p/zsVHW, CC-BY

Plastic bags in the ocean can be mistaken for food by an unsuspecting marine predator.

The size of the garbage patch is unknown, since it can't be seen from above. Some people estimate that it's twice the size of continental U.S, with a mass of 100 million tons.

Effect on Organisms

In some areas, plastics have seven times the concentration of zooplankton. This means that filter feeders are ingesting a lot of plastics. This may kill the organisms or the plastics may remain in their bodies. They are then eaten by larger organisms that store the plastics and may eventually die. Fish may eat organisms that have eaten plastic and then be eaten by people. This also exposes humans to toxic chemicals that the fish may have ingested with the plastic.

There are similar patches of trash in the gyre of the North Atlantic and Indian oceans. The Southern Hemisphere has less trash buildup because less of the region is continent.

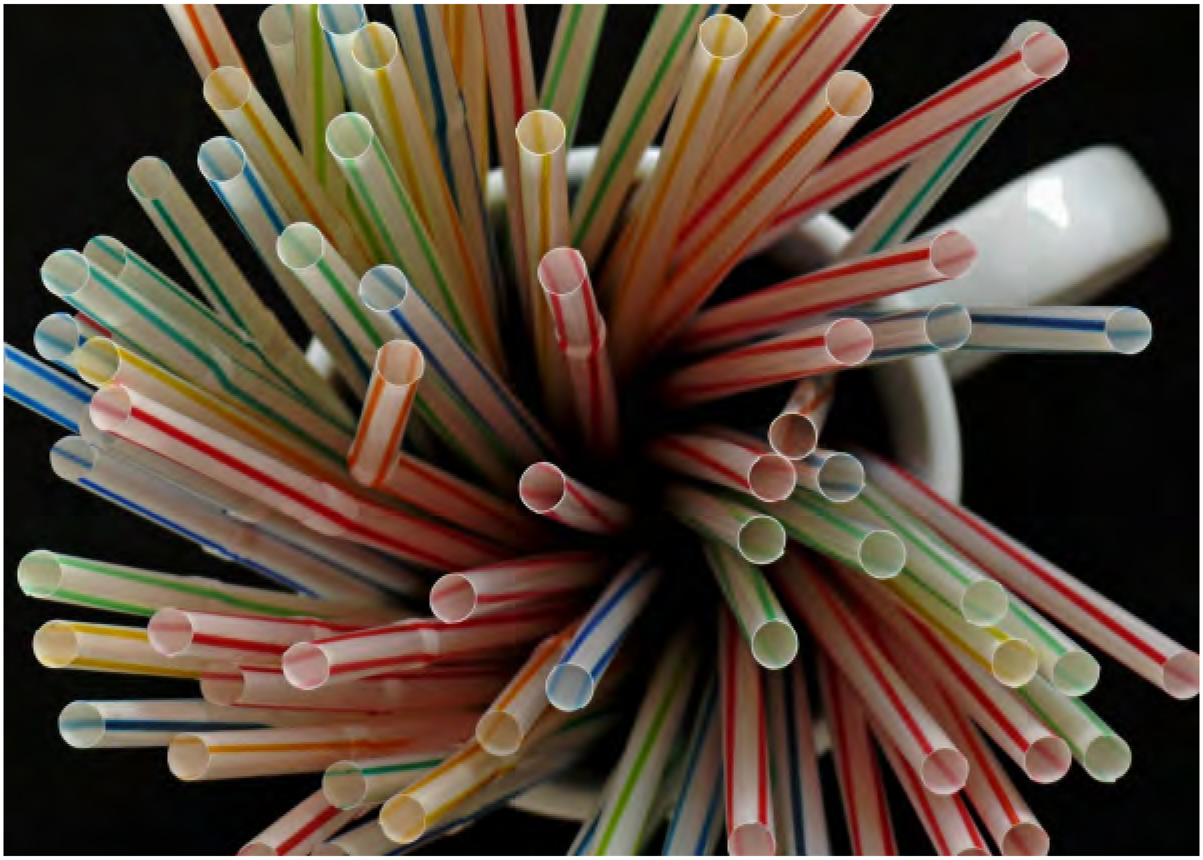
Summary

- Trash from land (80%) or human activities at sea (20%) ends up in the oceans; about 80% of this trash is plastic.
- Plastic trash does not usually biodegrade in the ocean but just forms tiny polymers that resemble plankton.
- Plastic pieces of trash and plastic molecules can kill marine organisms by becoming lodged in their digestive systems or by trapping them so they can't swim.

Review

1. How can plastic kill marine organisms?
2. Since plastic doesn't biodegrade in the oceans, what does the future hold? What can be done to make the future better?
3. Some people say that the Great Pacific Garbage Patch is a hoax. What can scientists do to show people that it is real?
4. Are there alternatives to plastic that have the same properties of plastic but are less harmful to the environment?
5. What are some solutions for reducing solid plastic waste?

Putting It Together



http://www.peakpx.com/411589/stripe-drinking-straw-lot, CC0

Chemistry has solved a lot of complex, real world problems. There have also been unintended consequences of man-made compounds.

1. Describe the ill effects or other of designed chemicals in Earth systems including ozone depletion and restoration, DDT, development of antibiotics and antibiotic resistance.

CHAPTER 4

Strand 4: Energy in Chemical Systems

Chapter Outline

Image by Steve Buissinne, pixabay.com, CC0

A system's total energy is conserved as energy is continually transferred from one particle to another and between its various possible forms. The energy of a system depends on the motion and interactions of matter and radiation within that system. When bonds are formed between atoms, energy is released. Energy must be provided when bonds are broken. When electromagnetic radiation with longer wavelengths is absorbed by matter, it is generally converted into thermal energy or heat. When visible light is absorbed by matter, it results in phenomena related to color. When shorter wavelength electromagnetic radiation is absorbed by matter, it can ionize atoms and cause damage to living cells. Nuclear processes, including fusion, fission, and radioactive decay of unstable nuclei, involve the release or absorption of large amounts of energy. Society's demand for energy requires thinking creatively about ways to provide energy that don't deplete limited resources or produce harmful emissions.

4.1 Reaction Energy (Chem.4.1)

Explore this Phenomenon

Chemical Reaction by Kate Ter Haar, https://flic.kr/p/9FY9gq, CC-BY

When mixed together, the temperature of a baking soda and vinegar mixture decreases to a temperature lower than either started with.

1. How does the baking soda and vinegar reaction involve energy?
2. What is happening inside of the mixture to cause the change in temperature?

Standard Chem.4.1

Construct an argument from evidence about whether a simple chemical reaction absorbs or releases energy. Emphasize that the overall change in energy is related to the energy absorbed when bonds are broken and the energy released when bonds are formed. Examples could include chemical reactions releasing or absorbing energy to or from the surrounding solution or the metabolism of glucose. (PS1.B, PS3.B)

In this section, pay attention to the energy changes involved in chemical reactions. Is energy being absorbed or released? How can you tell? How are the energy changes related to changes in bonds within molecules?

Energy is Conserved in All Changes

Energy is often divided into two general types: kinetic energy and potential energy. Kinetic energy is the energy of motion. In chemistry, typically kinetic energy is observed in the form of heat (change in temperature), light, or electricity. Potential energy is the energy of position or stored energy.

Molecules contain potential energy in their physical states and in their chemical bonds. When solid substances are changed into liquid, energy has to be added to provide the heat of melting. That energy was used to pull the molecules further apart, changing solid into liquid. That energy is then stored in the liquid as potential energy due to the greater distances between attracting molecules. For similar reasons, energy also has to be added to convert a liquid into a gas.

Chemical bonds store potential energy in a slightly different way. Potential energy is based on position or location. As two atoms form a bond and move closer together, there is less potential energy. The extra energy is typically given off as heat or light. When a bond is broken, the atoms move farther apart and the potential energy increases. The energy added typically comes from heat or light.

The Law of Conservation of Energy (energy cannot be created or destroyed) tells us that whatever energy there is in the beginning, there is an equal amount of energy at the end of any change. Although energy can change form between kinetic energy and potential energy, the amount of energy total does not change. The Law of Conservation of Energy is true in all chemical changes from burning gas in a furnace to metabolizing sugar in your body's cells.

All Chemical Reactions Involve Energy

Every system or sample of matter has energy stored in it. When chemical reactions occur, the new bonds formed never have exactly the same amount of potential energy as the bonds that were broken. Therefore, all chemical reactions involve energy changes. Energy is either given off to the surroundings or taken into the system by the reaction.

$NaCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + NaNO_3(aq) \quad \Delta H = -166\ kJ$

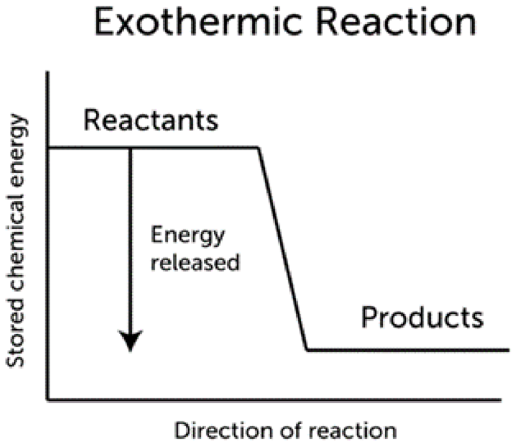
The equation above represents a chemical reaction where energy is produced. This means that there is less energy stored in the bonds of the products than there is in the bonds of the reactants. Therefore, extra energy is left over when the reactants become products.

What is an Exothermic Reaction?

All chemical reactions involve changes in energy. Energy is used to break bonds in reactants, and energy is released when new bonds form in the products. In some chemical reactions, called endothermic reactions, less energy is released when new bonds form in the products than is needed to break bonds in the reactants. The opposite is true of exothermic reactions. In an exothermic reaction, it takes less energy to break bonds in the reactants than is released when new bonds form in the products.

The word *exothermic* literally means "turning out heat". Energy, often in the form of heat, is released as an exothermic reaction proceeds. This is illustrated in the figure. The general equation for an exothermic reaction is:

Reactants→Products + Energy



If the energy produced in an exothermic reaction is released as heat, it results in a rise in temperature. As a result, the products are likely to be warmer than the reactants.

Another way by which chemists use to indicate energy change is to use the symbol ΔH. This symbol indicates the change in enthalpy of a reaction. For most purposes, we can think of this as the change in heat for a reaction. If a reaction releases heat (exothermic), ΔH will have a negative value.

Image by Alexis_Fotos, pixabay.com, CC0

All combustion reactions are exothermic reactions. During a combustion reaction, a substance burns as it combines with oxygen. When substances burn, they usually give off energy as heat and light. Look at the big bonfire in the Figure below. The combustion of wood is an exothermic reaction that releases a lot of energy as heat and light. You can see the light energy the fire is giving off. If you were standing near the fire, you would also feel its heat.

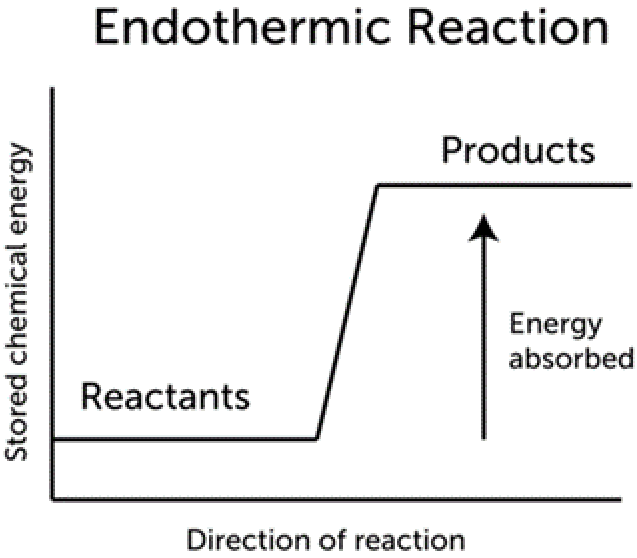
Energy Changes in Endothermic Reactions

Did you ever use an instant ice pack like? You don't have to pre-cool it in the freezer. All you need to do is squeeze the pack and it starts to get cold. How does this happen? The answer is an endothermic chemical reaction.

The word endothermic literally means "taking in heat". A constant input of energy, often in the form of heat, is needed to keep an endothermic reaction going. This is illustrated in the figure below. Energy must be constantly added because not enough energy is released when the products form to break more bonds in the reactants. The general equation for an endothermic reaction is:

$$\textbf{Reactants + Energy} \rightarrow \textbf{Products}$$

In endothermic reactions, the temperature of the products is typically lower than the temperature of the reactants. The drop in temperature may be great enough to cause liquids to freeze.



Q: Now can you guess how an instant cold pack works?
A: Squeezing the cold pack breaks an inner bag of water, and the water mixes with a chemical inside the pack. The chemical and water combine in an endothermic reaction. The energy needed for the reaction to take place comes from the water, which gets colder as the reaction proceeds.

Photosynthesis

One of the most important series of endothermic reactions is photosynthesis. In photosynthesis, plants make the simple sugar glucose ($C_6H_{12}O_6$) from carbon dioxide (CO_2) and water (H_2O). They also release oxygen (O_2) in the process. The reactions of photosynthesis are summed up by this chemical equation:

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

The energy for photosynthesis comes from light. Without light energy, photosynthesis cannot occur. As you can see in the image, plants can get the energy they need for photosynthesis from either sunlight or artificial light.

Image by Ulrike Leone, *pixabay.com, CC0*

Hydroponics! by Peter Kirn, https://flic.kr/p/96wiKw, CC-BY-SA

Example:

Which of the following processes are endothermic, and which are exothermic?

1. water boiling
2. gasoline burning
3. water vapor condensing
4. When barium hydroxide reacts with ammonium chloride, the temperature drops significantly
5. ice forming on a pond

Solution:

1. Endothermic – state change from liquid to a gas absorbs heat from the surroundings.
2. Exothermic – combustion releases heat to the surroundings.
3. Exothermic – state change from gas to a liquid releases heat to the surroundings.
4. Endothermic - the temperature drops because heat is absorbed from the surroundings
5. Exothermic – state change from liquid to a solid releases heat to the surroundings.

Practice

1. If a chemical reaction absorbs heat from the surroundings, it is said to be what?
   a. in equilibrium
   b. in a closed system
   c. an exothermic reaction
   d. an endothermic reaction

2. If a chemical reaction releases heat to the surroundings, it is said to be what?
   a. in equilibrium
   b. in a closed system
   c. an exothermic reaction
   d. an endothermic reaction

3. Which of the following processes would be endothermic?
   a. natural gas burning
   b. melting chocolate
   c. fireworks exploding
   d. steam condensing

4. Which of the following processes would be exothermic?
   a. gasoline burning
   b. evaporation of ether
   c. melting butter
   d. boiling water

5. What is an exothermic reaction?

6. Why are the products of an exothermic reaction likely to be warmer than the reactants?

7. What is an endothermic reaction?

8. Why is the temperature of products likely to be lower than the temperature of reactants in an endothermic reaction?

Putting It Together

Chemical Reaction by Kate Ter Haar, https://flic.kr/p/9FY9gq, CC-BY

Let us revisit this phenomenon:

When mixed together, the temperature of a baking soda and vinegar mixture decreases.

1. What would be the system and what would be the surroundings?
2. Is it endothermic or exothermic? Explain how you know.
3. How does the law of conservation of energy apply in this situation?

4.2 Electromagnetic Radiation (Chem.4.2)

Explore this Phenomenon

Image by Rodrigo Conceicao (visualworker), pixabay.com, CC0

You feel warmer in sunlight while wearing dark colored shirts than white colored shirts.

1. What are the interactions between sunlight and molecules in the two shirts that causes the temperature differences?
2. What about the molecules in the two different shirts causes them to have different colors?

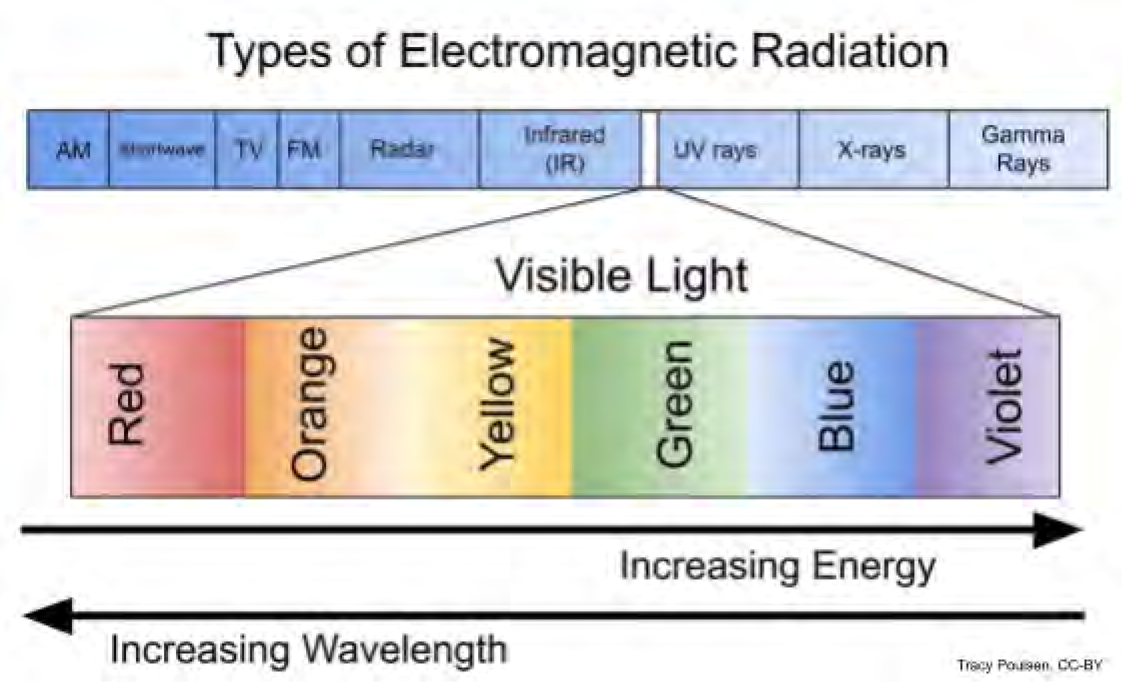
Standard Chem.4.2

Construct an explanation of the effects that different frequencies of electromagnetic radiation have when absorbed by matter. Emphasize a qualitative understanding. Examples could include that low energy electromagnetic radiation can increase molecular rotation and bond vibration, visible light can cause electronic transitions, and high energy electromagnetic radiation can result in ionization and bond breaking. (PS4.B)

In this section, pay attention to how the frequency of electromagnetic radiation effects matter when it is absorbed. Notice how light affects molecules, electrons, and other forms of matter.

Energy and Frequency

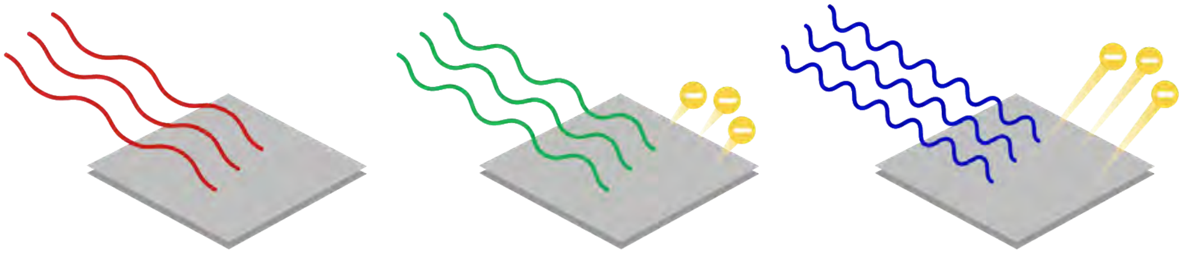
Visible light and infrared light are just a small part of the full range of electromagnetic radiation which is organized on the electromagnetic spectrum. You can see the waves of the electromagnetic spectrum in the Figure below. At the top of the diagram, the wavelengths of the waves are given. Also included are objects that are about the same size as the corresponding wavelengths. The frequencies and energy levels of the waves are shown at the bottom of the diagram. Some sources of the waves are also given.



Tracy Poulsen, CC-BY

Light frequency and the threshold frequency

We can think of the incident light as a stream of photons with an energy determined by the light frequency. When a photon hits the metal surface, the photon's energy is absorbed by an electron in the metal. The graphic below illustrates the relationship between light frequency and the kinetic energy of ejected electrons.



The frequency of red light (left) is less than the threshold frequency of this metal ($\nu_{\text{red}} < \nu_0$), so no electrons are ejected. The green (middle) and blue light (right) have $\nu > \nu_0$, so both cause photoemission. The higher energy blue light ejects electrons with higher kinetic energy compared to the green light.

The scientists observed that if the incident light has a frequency less than a minimum frequency, then no electrons were ejected regardless of the light amplitude. This minimum frequency is also called the *threshold frequency*, and its value depends on the metal. For frequencies greater than the threshold frequency, electrons would be ejected from the metal.

Rotation and Vibration - Larger Frequencies (IR to Microwave)

When a molecule absorbs light that does not have enough energy to excite electrons or remove electrons, the molecule will move in different ways based on the amount of energy absorbed (figure above). These movements cause the temperature of the substance to increase.

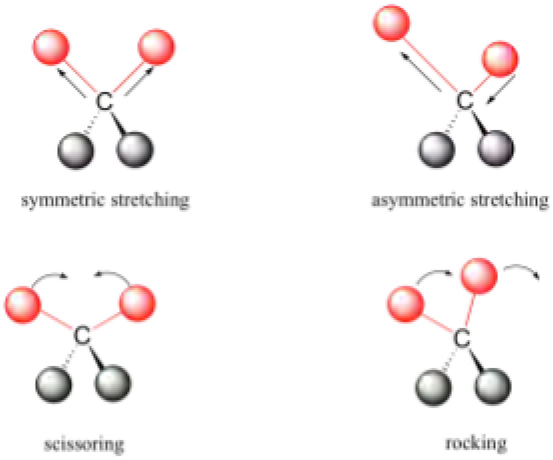


Image from https://chem.libretexts.org/Courses/University_of_California_Davis/UCD_Chem_002CH/Text/UNIT_IV%3A_MOLECULAR_SPECTROSCOPY/20.2%3A_Vibrations_and_Rotations_of_Molecules%3A_Infrared_and_Microwave_Spectroscopy, CC-BY-NC-SA 3.0

Electron Transitions - Visible Frequencies

When a molecule absorbs light that has enough energy to excite electrons (move them to higher energy values) it will appear as a colored compound. For example, chlorophyll absorbs red and blue light, leaving green light visible (figure below).

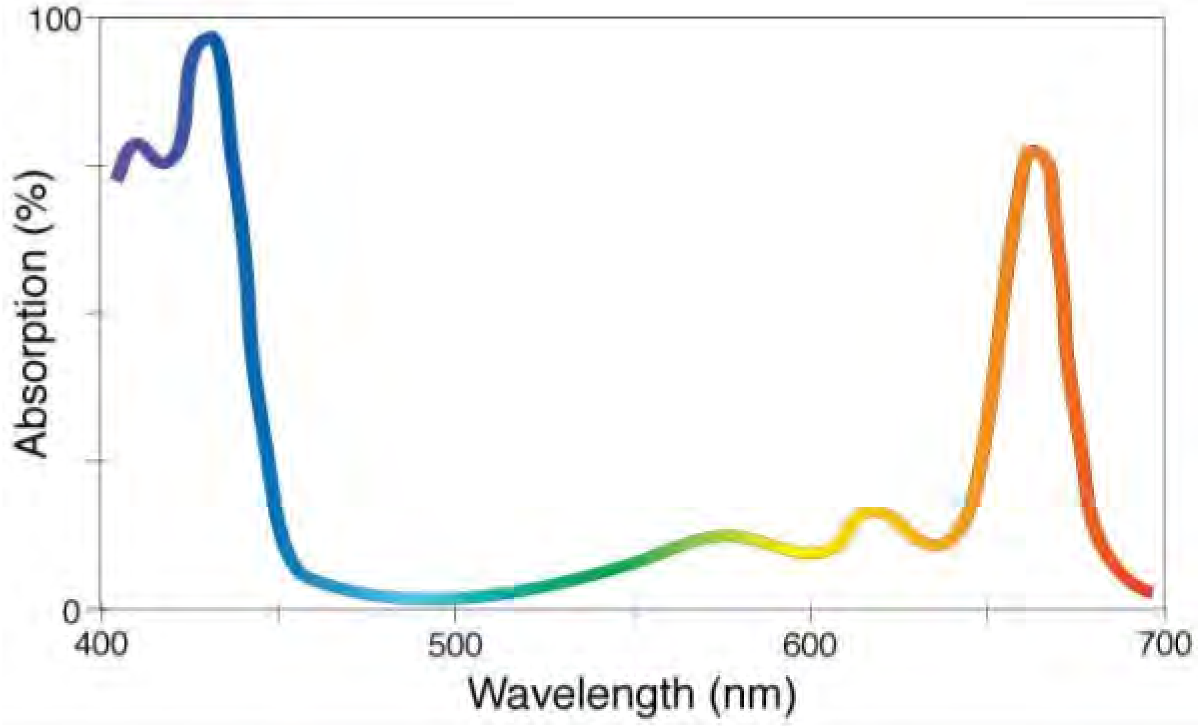
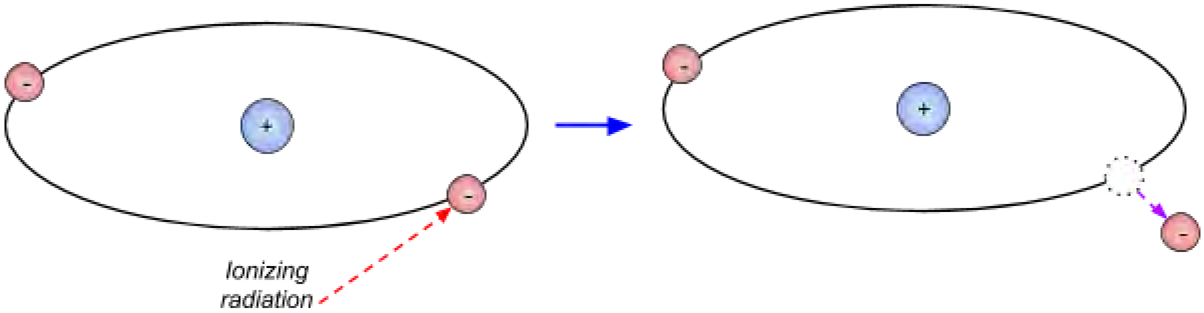


Image from https://www.giss.nasa.gov/research/features/201311_kiang/, public domain

Ionization - Smaller Frequencies



High energy light causes electrons to be ejected and frequently destroys the structure of molecules. An example of this is UV light causing sunburns - the light has enough energy to remove electrons from the molecules in skin. If enough electrons are removed from the molecules in different cells then the cells will die.

Putting It Together

Image by Rodrigo Conceicao (visualworker), pixabay.com, CC0

Let us revisit this phenomenon:

You feel warmer in sunlight while wearing dark colored shirts than white colored shirts.

1. How does the light absorption affect the temperature you feel?
2. How does the different light being absorbed affects the thermal energy?

4.3 Energy Conversion (Chem.4.3)

Explore this Phenomenon

By OpenStax, https://cnx.org/contents/havxkyvS, CC-BY 4.0

Ouch = Rolled Ankle by John M, https://flic.kr/p/5WgVWw, CC-BY-SA

Have you ever used a cold pack?

1. When would a person use a cold pack?
2. What form of energy is being demonstrated?
3. What kind of reaction would cause this cold sensation?

Standard Chem.4.3

Design a device that converts energy from one form into another to solve a problem. *Define the problem, identify criteria and constraints, develop possible solutions using models, analyze data to make improvements from iteratively testing solutions, and optimize a solution.* Emphasize chemical potential energy as a type of stored energy. Examples of sources of chemical potential energy could include oxidation-reduction or combustion reactions. (PS3.B, ETS1.A, ETS1.B, ETS1.C)

In this section, pay attention to how energy flows in and out of systems. In particular, think about how to convert energy from one form to another to solve a problem. Use your understanding of energy changes to explain the limitations and possibles of a device that converts one form of energy into another.

What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of stems:

1. Identifying the problem and defining criteria and constraints.
2. Generating ideas for how to solve the problem. Engineers can use research, brainstorming and collaboration with others to come up with ideas for solutions and designs.
3. Build and then test the prototypes. Using data collected, the engineer can analyze how well the various prototypes meet the given criteria and constraints.
4. Evaluate what is needed to improve the leading design or devise a better one.

To design a solution to the problem, you will need to start by identifying the criteria and constraints. Then develop several possible solutions. Once you have several possible solutions, use the criteria and constraints to evaluate each. You should test the solution that will best meet the criteria and constraints, and then determine how to improve the solution, based on test results. Testing the solution may include modeling, working with materials, using mathematical relationships, etc.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

1. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria

and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).

2. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Which type of engineering task is utilized in this SEEd Standard?

As you learned in section 4.1 all chemical reactions involve changes in energy. Energy can be absorbed in an endothermic reaction and it feels cold or released in an exothermic reaction and you will feel heat. Remember that the energy involved comes from the breaking of bonds in reactants and the formation of new bonds in the products.

The reactions above describe a form of energy called thermal energy. There are several other forms of energy, though, including electrical energy, kinetic energy, mechanical energy and chemical potential energy. Each form produces energy in its own way and some forms store energy while other energies cause change.

One of the challenges where you live today is how to benefit from the available energy efficiently. Your cell phone uses rechargeable batteries, your automobile uses fuel, your refrigerator keeps things cold, and people use ice packs to keep things cold or to soothe muscle pain.

One constraint is how we get one form of energy to change into a different form of energy. For example, how does the refrigerator use electricity to keep things cold or how does your car use chemical potential energy from the fuel to cause your car to move?

An individual might use a chemical ice pack on their sore muscles to cool or soothe them. The pack contains reactants separated from each other. When you can break the barrier and allow the reactants to mix and endothermic reaction occurs. Common reactants in the ice pack include water and ammonium nitrate, water and ammonium chloride, or water and potassium chloride.

Other ice packs are gel-based using substances like water and rubbing alcohol to produce a material that stays cold for extended periods of time. Each of these methods are simple designs that will convert chemical potential energy to thermal energy (or the lack thereof) that can be created to help a person with sore muscles.

Putting It Together

Changing States by Kurt Bauschardt, https://flic.kr/p/WtrvoA, CC-BY-SA

sciencel by delgrosso, https://flic.kr/p/7Ae6Mf, BY-NC-ND

There are many useful designs that can convert one form of energy to another, including the production of a homemade battery, the use of steam and other fuels to power an engine, or the burning of wood to create heat.

1. What device could you design as a way to convert energy from one form to another?

4.4 Nuclear Energy (Chem.4.4)

Explore this Phenomenon

Explosion of Dynamite

Explosion of Nuclear Bomb

(top) Image by U.S. Navy photo by Mass Communication Specialist 2nd Class Aaron Burden, public domain

(right) Image by vaXzine, https://flic.kr/p/6h4gtf, CC-BY-NC-ND

Chemical reactions and nuclear reactions can both release energy. In the pictures above there is an example of a chemical reaction and a nuclear reaction.

1. What is happening inside of a chemical reaction to produce energy?
2. What is happening inside of a nuclear reaction to produce energy?
3. Predict which type of reaction you expect to release more energy.

Standard Chem.4.4

Use models to describe the changes in the composition of the nucleus of the atom during nuclear processes, and compare the energy released during nuclear processes to the energy released during chemical processes. Emphasize a qualitative understanding of nuclear changes. Examples of nuclear processes could include the formation of elements through fusion in stars, generation of electricity in a nuclear power plant, radioactive decay, or the use of radioisotopes in nuclear medicine. (PS1.C, PS3.D)

In this section, pay attention to the energy changes involved with nuclear processes. Look for ways that models explain the energy changes involved in nuclear processes. Pay attention to the amount of energy released during chemical reactions compared to the amount of energy released during nuclear reactions.

All chemical reactions involve energy.

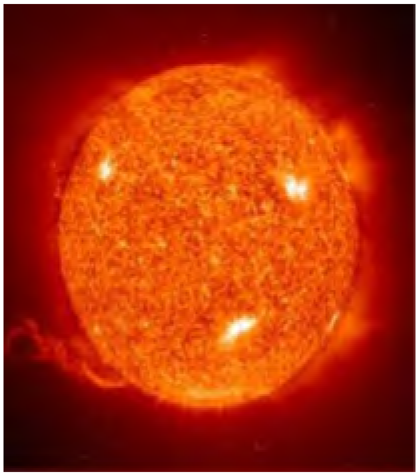
Energy is used to break bonds in reactants, and energy is released when new bonds form in the products. The amount of energy needed or released depends upon the structure of the molecules that are involved in the reaction. Some reactions need to be heated for long periods of time in order for change to take place. Other reactions release energy, allowing heat to be given off to the surroundings.

Chemical potential energy is the energy stored in the chemical bonds of a substance. The various chemicals that make up gasoline contain a large amount of chemical potential energy that is released when the gasoline is burned in a controlled way in the engine of the car. The release of that energy does two things. Some of the potential energy is transformed into work, which is used to move the car. At the same time, some of the potential energy is converted to heat, making the car's engine very hot. The energy changes in a system occur as either heat or work, or some combination of both.

Image by Skeeze, pixabay.com, CC0

A dragster is able to accelerate because of the chemical potential energy of its fuel. The burning of the fuel also produces large amounts of heat.

Nuclear energy is the energy stored in the nucleus of an atom. This Energy can be released through fusion or fission.



The sun is basically a giant ball of hydrogen gas undergoing fusion and giving off vast amounts of energy in the process.
Source: NASA (public domain)

Fusion is the act of forcing atoms together. This results in tighter packing and the release of energy. As seen in this Figure, energy is released in the formation of the larger atom, helium (He) from the fusion of hydrogen-2 and hydrogen-3 as well as from the expulsion of a neutron. This fusion is happening in the core of the sun.

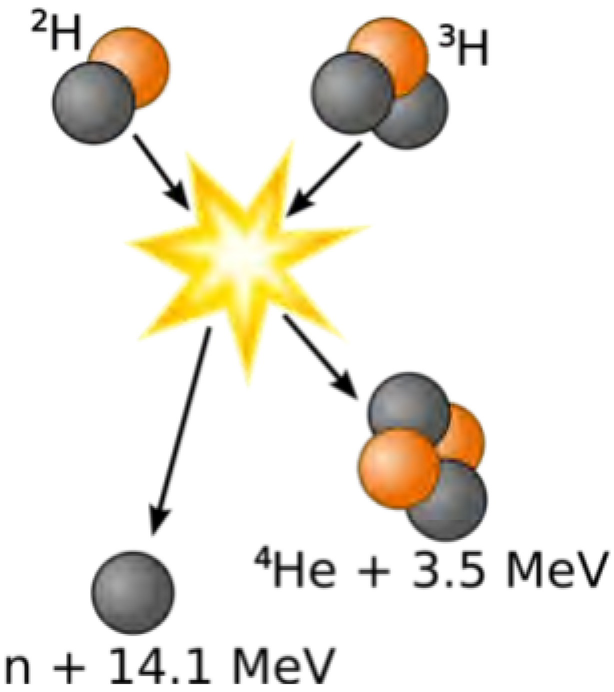


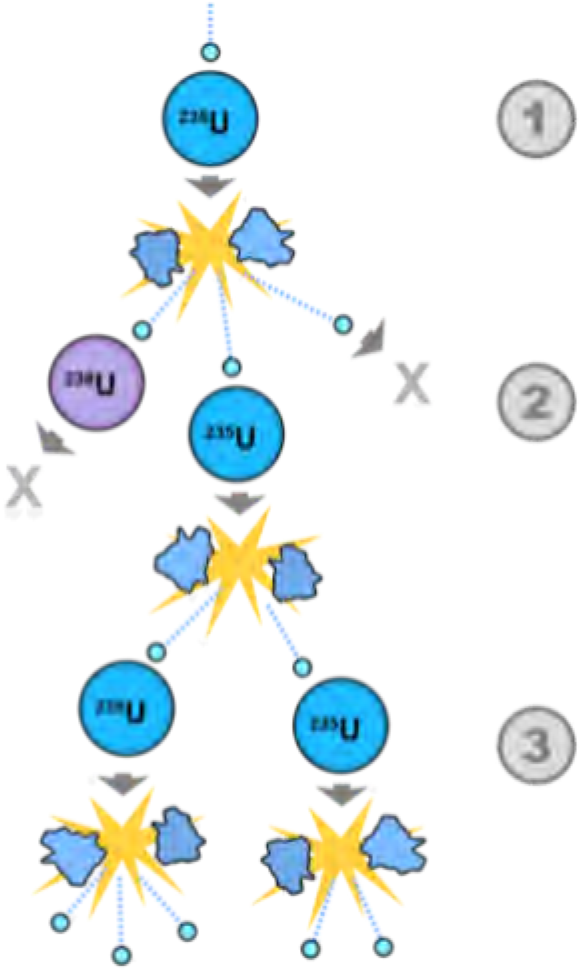
Image by Wykis, https://commons.wikimedia.org/wiki/File:Deuterium-tritium_fusion.svg, CC0

Nuclear fusion reaction between deuterium and tritium.

Nuclear fusion reactions in the laboratory have been extraordinarily difficult to achieve. Extremely high temperatures (millions of degrees) are required. Methods must be developed to force the atoms together and hold them together long enough to react. The neutrons released during the fusion reactions can interact with atoms in the reactor and convert them to radioactive materials. There has been some success in the field of nuclear fusion reactions, but the journey to feasible fusion power is still a long and uncertain one.

Enormous nuclear energy is also present in the bonds that hold the nucleus together. This nuclear energy can be released when those bonds are broken. The bonds can be broken through nuclear fission. In nuclear fission, atoms are split apart to form smaller atoms, releasing energy.

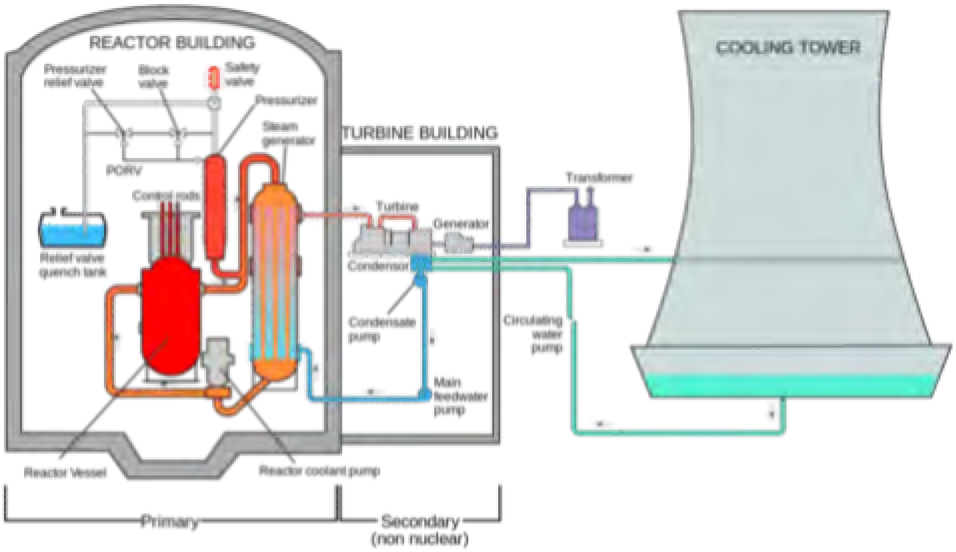
In nuclear fission, atoms are split apart, which releases energy. All nuclear power plants use nuclear fission, and most nuclear power plants use uranium atoms. During nuclear fission, a neutron collides with a uranium atom and splits it, releasing a large amount of energy in the form of heat and radiation. More neutrons are also released when a uranium atom splits. These neutrons continue to collide with other uranium atoms, and the process repeats itself over and over again. This process is called a nuclear chain reaction. This reaction is controlled in nuclear power plant reactors to produce a desired amount of heat.



https://commons.wikimedia.org/wiki/File:Fission_chain_reaction.svg, *CC0*

The next figure shows the layout of a typical nuclear power plant. The radioactive rods are in the red container along with water, which is heated to steam. The energy for this heat comes from fission reactions of uranium. The steam passes through the turbine and causes the turbine to spin, generating electricity. As the steam condenses, it is run through a cooling tower to lower its temperature. The water then recirculates through the reactor core to be used again.

The control rods play an important role in the modulation of the nuclear chain reaction (usually a collision of a neutron with uranium). Each collision produces more neutrons than were present initially. If left unsupervised, the reaction would soon get out of control. Rods are commonly made of boron or a number of metals and metal alloys. The purpose of the control rods is to absorb neutrons to regulate the rate of the chain reaction so that the water does not overheat and destroy the reactor.



https://commons.wikimedia.org/wiki/File:Tmi-2_schematic_revised.svg, CC0

Schematic for a nuclear power plant.

When we compare chemical and nuclear potential energy the difference is astounding. The amount of energy produced with uranium-235 is 80 *million* KJ/g, while coal is 1-30 KJ/g and natural gas (methane) is 50-55 KJ/g. In a nuclear power plant uranium fuel is formed into a 6 gram ceramic pellets. Each ceramic pellet produces about the same amount of energy as 150 gallons of oil. These energy-rich pellets are stacked end-to-end in 12-foot metal fuel rods. A bundle of fuel rods, some with hundreds of rods, is called a fuel assembly. A reactor core contains many fuel assemblies.

Putting It Together

Explosion of Dynamite

(top) Image by U.S. Navy photo by Mass Communication Specialist 2nd Class Aaron Burden, public domain

Explosion of Nuclear Bomb

(right) Image by vaXzine, https://flic.kr/p/6h4gtf, CC-BY-NC-ND

Let us revisit this phenomenon:

Chemical reactions and nuclear reactions can both release energy. In the pictures above there is an example of a chemical reaction and a nuclear reaction.

1. Does a chemical reaction release more or less energy than nuclear reactions?
2. Which is a more efficient source of energy: chemical or nuclear processes? You could compare the chemical reaction of burning fossil fuels versus the use of uranium in nuclear power plants.

4.5 Societal Energy (Chem.4.5)

Explore this Phenomenon

Adapted from "Utah counties", https://en.wikipedia.org/wiki/Utah, CC-BY-SA.

The Blue Castle Project is a proposed nuclear power plant near Green River, Utah, United States. Projected for completion in 2030, it will have two 1500 megawatt reactors. Originally proposed in 2007 and after winning a three-year legal battle over water rights, Blue Castle began reviewing construction companies to work on building the plant.

Public reaction has varied since the project was originally proposed. There are several local and national environmental groups who oppose the project.

The plant is projected to "increase Utah's electrical capacity by approximately 50 percent".[5] Utah Senator Bob Bennett stated in late 2008 that "if we are going to be serious about carbon emissions, we have to have a much larger nuclear component in our electric production" in November 2008.[26] The plant was proposed in part to support a projected 2016 need for power from Rocky Mountain Power, the main supplier of electrical power to the state of Utah.[3] Jon Huntsman Jr., the governor of Utah at that time, stated that he was opposed to any plan for a plant that did not include onsite spent fuel reprocessing.[2]

BCH projects about $500 million annually in revenue and state and local taxes paid.[4] The project is projected to cost up to $20 billion, though BCH projected only $13.4 billion as of January 2017. The plant is expected to produce up to 4000 short term jobs during construction and about 1000 long term jobs in the Green River area.

1. Why would several local and national environmental groups oppose the project?
2. What does Senator Bob Bennett mean by "be serious about carbon emissions"?
3. Why does Rocky Mountain Power have a need for more power?
4. Where will our energy come from if the nuclear power plant isn't built?
5. What advantages could come to our state from this nuclear power plant?
6. What disadvantages could come to our state from this nuclear power plant?

Standard Chem.4.5

Develop an argument from evidence to evaluate a proposed solution to societal energy demands *based on prioritized criteria and trade-offs that account for a range of constraints that could include cost, safety, reliability, as well as possible social, cultural, and environmental impacts.* (PS3.D, ETS1.A, ETS1.B, ETS1.C)

In this section, think about proposed solutions to meet society's energy demands. Pay attention to the prioritized criteria and tradeoffs of the proposed solution. For example, your proposed solution should consider cost, safety, reliability, social, cultural, and environmental impacts.

What is involved in Engineering Design?

Engineering is a creative process where each new version of a design is tested and then modified, based on what has been learned up to that point. This process includes a number of stems:

1. Identifying the problem and defining criteria and constraints.
2. Generating ideas for how to solve the problem. Engineers can use research, brainstorming and collaboration with others to come up with ideas for solutions and designs.
3. Build and then test the prototypes. Using data collected, the engineer can analyze how well the various prototypes meet the given criteria and constraints.
4. Evaluate what is needed to improve the leading design or devise a better one.

To design a solution to the problem, you will need to start by identifying the criteria and constraints. Then develop several possible solutions. Once you have several possible solutions, use the criteria and constraints to evaluate each. You should test the solution that will best meet the criteria and constraints, and then determine how to improve the solution, based on test results. Testing the solution may include modeling, working with materials, using mathematical relationships, etc.

In the Science with Engineering Education (SEEd) Standards, specific engineering standards generally involve two types of tasks:

1. If the standard includes the idea of designing, then the design process will contain components of defining the problem (along with identifying the criteria and constraints), developing many possible solutions, and optimizing a solution (e.g., determining a best solution for the situation based on the criteria and constraints, testing the solution, refining the solution).

2. If the standard includes the idea of evaluating, then the design process will contain components of defining the problem (along with identifying the criteria and constraints) and optimizing a solution. The idea of developing many possible solutions is not included because various solutions will be provided. The idea of evaluating then means determining a best solution from the provided solutions for the situation based on meeting the criteria and constraints requirements.

Which type of engineering task is utilized in this SEEd Standard?

This section is from the Energy Information Administration. For more information, go to: https://www.eia.gov/energyexplained/us-energy-facts/

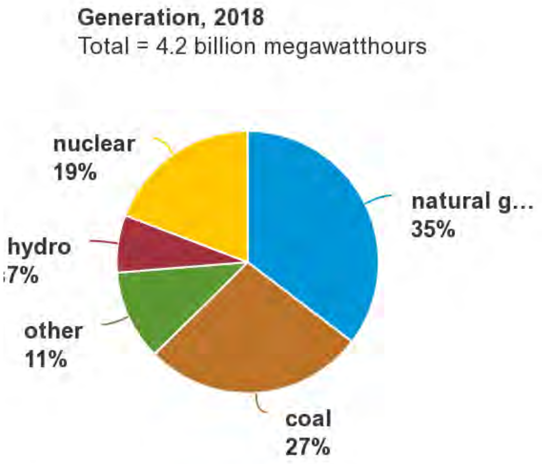
The United States uses a mix of energy sources

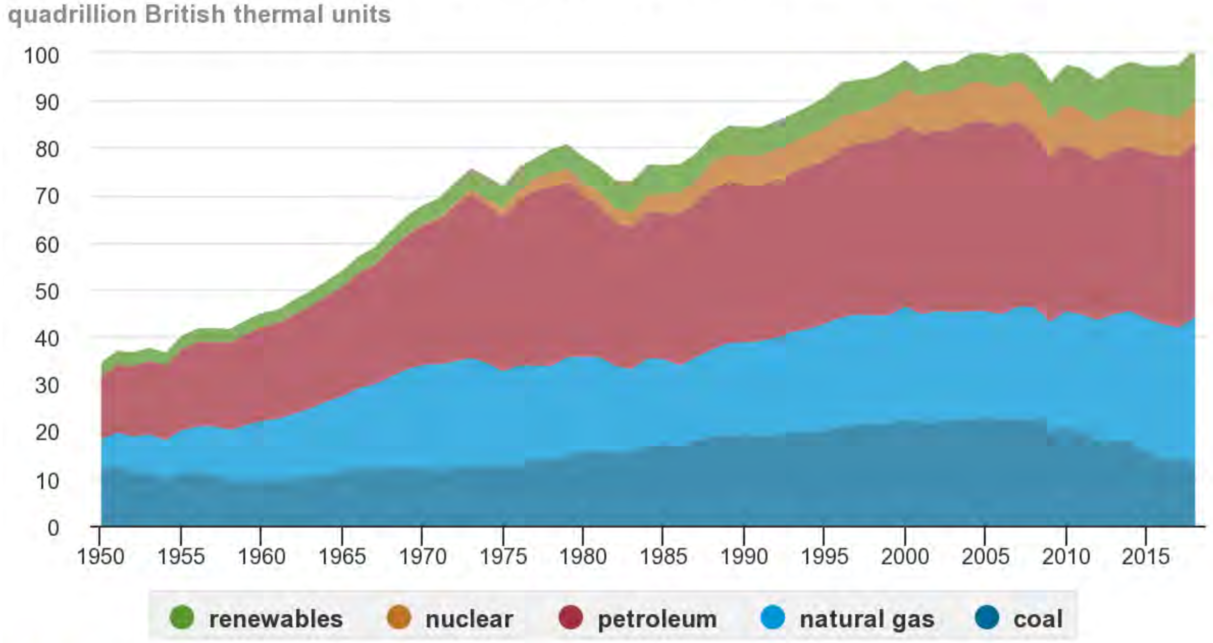
Fossil fuels have dominated the U.S. energy source for more than 100 years. However, considering it is a nonrenewable source and the environmental issues related to burning fossil fuels other sources of energy must be considered.

The United States uses and produces many different types and sources of energy, which can be grouped into general categories such as primary and secondary, renewable and nonrenewable, and fossil fuels.

Primary energy sources include fossil fuels (petroleum, natural gas, and coal), nuclear energy, and renewable sources of energy. Electricity is a secondary energy source that is generated (produced) from primary energy sources.

Note: Capacity is net summer capacity. Generation is from utility-scale generators. Hydro is conventional hydroelectric. Totals may not equal sum of components because of independent rounding.
Source: U.S. Energy Information Administration, *Electric Power Monthly*, March 2019, preliminary data

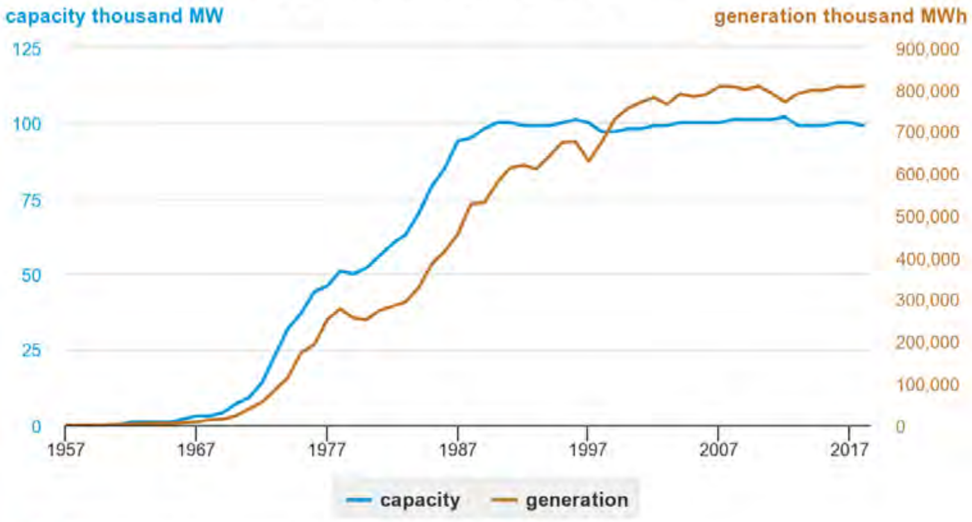




U.S. primary energy consumption by major sources, 1950-2018

Note: Petroleum is petroleum products excluding biofuels, which are included in renewables.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3, April 2019

Nuclear power plants generate about 20% of U.S. electricity
As of January 1, 2019, 98 nuclear reactors were operating at 60 nuclear power plants in 30 states. Thirty-six of the plants have two or more reactors. Nuclear power has supplied about one-fifth of total annual U.S. electricity since 1990.



U.S. nuclear electricity generation capacity and generation, 1957-2018

Note: Capacity is net summer; MW is megawatts; MWh is megawatthours.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 8.1, March 2019

The United States generates more nuclear power than any other country

In 2016, 31 countries had commercial nuclear power plants, and in 15 of the countries, nuclear energy supplied at least 20% of their total annual electricity generation. The United States had the largest nuclear electricity generation capacity and generated more nuclear electricity than any other country. France, with the second-largest nuclear electricity generation capacity and second-highest nuclear electricity generation, had the largest share—about 73%—of total annual electricity generation from nuclear energy.

Top five nuclear electricity generation countries, 2016

Country	Nuclear electricity generation capacity (million kilowatts)	Nuclear electricity generation (billion kilowatt hours)	Nuclear share of country's total electricity generation
United States	99.6	805.7	19.7%
France	63.1	386.5	73.0%
China	31.4	197.8	3.4%
Russia	26.1	184.1	17.8%
South Korea	23.1	154.3	29.3%

Source: U.S. Energy Information Administration, International Energy Statistics, as of June 17, 2019

Nuclear reactors and power plants have complex safety and security features

An uncontrolled nuclear reaction in a nuclear reactor could result in widespread contamination of air and water. The risk of this happening at nuclear power plants in the United States is small because of the diverse and redundant barriers and safety systems in place at nuclear power plants, the training and skills of the reactor operators, testing and maintenance activities, and the regulatory requirements and oversight of the U.S. Nuclear Regulatory Commission. A large area surrounding a nuclear power plant is restricted and guarded by armed security teams. U.S. reactors also have containment vessels that are designed to withstand extreme weather events and earthquakes.

Nuclear power reactors do not produce direct carbon dioxide emissions

Unlike fossil fuel-fired power plants, nuclear reactors do not produce air pollution or carbon dioxide while operating. However, the processes for mining and refining uranium ore and making reactor fuel all require large amounts of energy. Nuclear power plants also have large amounts of metal and concrete, which require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore, or if fossil fuels are used when constructing the nuclear power plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.

Nuclear energy produces radioactive waste

A major environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials can remain radioactive and dangerous to human health for thousands of years. Radioactive wastes are subject to special regulations that govern their handling, transportation, storage, and disposal to protect human health and the environment. The U.S. Nuclear Regulatory Commission (NRC) regulates the operation of nuclear power plants.

Spent reactor fuel storage and reactor decommissioning

Spent reactor fuel assemblies are highly radioactive and, initially, must be stored in specially designed pools of water. The water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. The United States does not currently have a permanent disposal facility for high-level nuclear waste.

When a nuclear reactor stops operating, it must be decommissioned. Decommissioning involves safely removing from service the reactor and all equipment that has become radioactive and reducing radioactivity to a level that permits other uses of the property. The U.S. Nuclear Regulatory Commission has strict rules governing nuclear power plant decommissioning that involve cleanup of radioactively contaminated power plant systems and structures and removing the radioactive fuel.

Putting It Together

Solar panels by Emily, https://flic.kr/p/ajCeEs, CC-BY-NC-ND

Idaho Wind Farm by Jerry and Pat Donaho, https://flic.kr/p/28CFrGZ, CC-BY-NC-ND

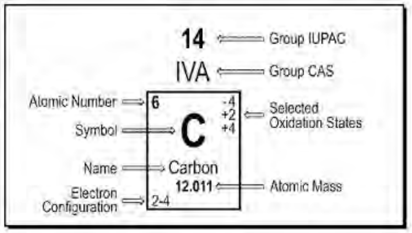
Oil refinery demolition Coryton by Sludge G, https://flic.kr/p/Jz8ohL, CC-BY-SA

https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_sum/html/rank_use_capita.html&sid=US source for data

Utah's Energy Consumption Estimates per Capita in 2017 was 267 million Btu. While there are 32 states that use more energy per capita than Utah, it is still a major concern given the growing population and increasing energy demands. There are multiple sources for energy production such as nuclear power, fossil fuels, renewable energy, etc.

1. Develop an argument for or against a specific energy source to meet our energy demands with specific evidence that could include cost, safety, reliability, as well as possible social, cultural, and environmental impacts.

PERIODIC TABLE OF THE ELEMENTS



	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H +1 -1 Hydrogen 1.0079 1																	2 He 0 Helium 4.0026 2
2	3 Li +1 Lithium 6.941 2-1	4 Be +2 Beryllium 9.0122 2-2											5 B +3 Boron 10.811 2-3	6 C -4 +2 +4 Carbon 12.011 2-4	7 N -3 -2 -1 +1 +2 +3 +4 +5 Nitrogen 14.007 2-5	8 O -2 Oxygen 15.999 2-6	9 F -1 Fluorine 18.998 2-7	10 Ne 0 Neon 20.179 2-8
3	11 Na +1 Sodium 22.990 2-8-1	12 Mg +2 Magnesium 24.305 2-8-2											13 Al +3 Aluminium 26.982 2-8-3	14 Si -4 +2 +4 Silicon 28.086 2-8-4	15 P -3 +3 +5 Phosphorus 30.974 2-8-5	16 S -2 +4 +6 Sulphur 32.065 2-8-6	17 Cl -1 +1 +3 +5 +7 Chlorine 35.453 2-8-7	18 Ar 0 Argon 39.948 2-8-8
4	19 K +1 Potassium 39.098 2-8-8-1	20 Ca +2 Calcium 40.078 2-8-8-2	21 Sc +3 Scandium 44.956 2-8-9-2	22 Ti +2 +3 +4 Titanium 47.867 2-8-10-2	23 V +2 +3 +4 +5 Vanadium 50.942 2-8-11-2	24 Cr +2 +3 +6 Chromium 51.996 2-8-13-1	25 Mn +2 +3 +4 +7 Manganese 54.938 2-8-13-2	26 Fe +2 +3 Iron 55.845 2-8-14-2	27 Co +2 +3 Cobalt 58.933 2-8-15-2	28 Ni +2 +3 Nickel 58.693 2-8-16-2	29 Cu +1 +2 Copper 63.546 2-8-18-1	30 Zn +2 Zinc 65.39 2-8-18-2	31 Ga +3 Gallium 69.723 2-8-18-3	32 Ge -4 +2 +4 Germanium 72.64 2-8-18-4	33 As -3 +3 +5 Arsenic 74.922 2-8-18-5	34 Se -2 +2 +6 Selenium 78.96 2-8-18-6	35 Br -1 +1 +5 Bromine 79.904 2-8-18-7	36 Kr 0 +2 Krypton 83.80 2-8-18-8
5	37 Rb +1 Rubidium 85.468 2-8-18-8-1	38 Sr +2 Strontium 87.62 2-8-18-8-2	39 Y +3 Yttrium 88.906 2-8-18-9-2	40 Zr +4 Zirconium 91.224 2-8-18-10-2	41 Nb +3 +5 Niobium 92.906 2-8-18-12-1	42 Mo +3 +6 Molybdenum 95.94 2-8-18-13-1	43 Tc +4 +6 +7 Technetium (98) 2-8-18-14-1	44 Ru +3 Ruthenium 101.07 2-8-18-15-1	45 Rh +3 Rhodium 102.91 2-8-18-16-1	46 Pd +2 +4 Palladium 106.42 2-8-18-18	47 Ag +1 Silver 107.87 2-8-18-18-1	48 Cd +2 Cadmium 112.41 2-8-18-18-2	49 In +3 Indium 114.82 2-8-18-18-3	50 Sn +2 +4 Tin 118.71 2-8-18-18-4	51 Sb -3 +3 +5 Antimony 121.76 2-8-18-18-5	52 Te -2 +4 +6 Tellurium 127.60 2-8-18-18-6	53 I -1 +1 +5 +7 Iodine 126.90 2-8-18-18-7	54 Xe 0 +2 +4 +6 Xenon 131.29 2-8-18-18-8
6	55 Cs +1 Cesium 132.91 2-8-18-18-8-1	56 Ba +2 Barium 137.33 2-8-18-18-8-2	57-71 La Lanthanide	72 Hf +4 Hafnium 178.49 2-8-18-32-10-2	73 Ta +5 Tantalum 180.95 2-8-18-32-11-2	74 W +6 Tungsten 183.84 2-8-18-32-12-2	75 Re +4 +6 +7 Rhenium 186.21 2-8-18-32-13-2	76 Os +3 +4 Osmium 190.23 2-8-18-32-14-2	77 Ir +3 +4 Iridium 192.22 2-8-18-32-15-2	78 Pt +2 +4 Platinum 195.08 2-8-18-32-17-1	79 Au +1 +3 Gold 196.97 2-8-18-32-18-1	80 Hg +1 +2 Mercury 200.59 2-8-18-32-18-2	81 Tl +1 +3 Thallium 204.38 2-8-18-32-18-3	82 Pb +2 +4 Lead 207.2 2-8-18-32-18-4	83 Bi +3 +5 Bismuth 208.98 2-8-18-32-18-5	84 Po +2 +4 Polonium (209) 2-8-18-32-18-6	85 At Astatine (210) 2-8-18-32-18-7	86 Rn 0 Radon (222) 2-8-18-32-18-8
7	87 Fr +1 Francium (223) -18-32-18-8-1	88 Ra +2 Radium (226) -18-32-18-8-2	89-103 Ac Actinide	104 Rf Rutherfordium (261) -18-32-32-10-2	105 Db Dubnium (262) -18-32-32-11-2	106 Sg Seaborgium (266) -18-32-32-12-2	107 Bh Bohrium (264) -18-32-32-13-2	108 Hs Hassium (277) -18-32-32-14-2	109 Mt Meitnerium (268) -18-32-32-15-2	110 Uun +2 +4 Ununnilium (281) -18-32-32-17-1	111 Uuu Unununium (272) -18-32-32-18-1	112 Uub Ununbium (285) -18-32-32-18-2	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (291)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

Electron Shells

1	K	2	s 2	P	D	F
2	L	8	2	6		
3	M	18	2	6	10	
4	N	32	2	6	10	14
5	O	32	2	6	10	14
6	P	18	2	6	10	
7	Q	8	2	6		
8	R	2	2			

Lanthanide

57 La +3 Lanthanium 138.91 2-8-18-18-9-2	58 Ce +3 +4 Cerium 140.12 2-8-18-20-8-2	59 Pr +3 Praseodymium 140.91 2-8-18-21-8-2	60 Nd +3 Neodymium 144.24 2-8-18-22-8-2	61 Pm +3 Promethium (145) 2-8-18-23-8-2	62 Sm +2 +3 Samarium 150.36 2-8-18-24-8-2	63 Eu +2 +3 Europium 151.96 2-8-18-25-8-2	64 Gd +3 Gadolinium 157.25 2-8-18-25-9-2	65 Tb +3 Terbium 158.93 2-8-18-27-8-2	66 Dy +3 Dysprosium 162.50 2-8-18-28-8-2	67 Ho +3 Holmium 164.93 2-8-18-29-8-2	68 Er +3 Erbium 167.26 2-8-18-30-8-2	69 Tm +3 Thulium 168.93 2-8-18-31-8-2	70 Yb +2 +3 Ytterbium 173.04 2-8-18-32-8-2	71 Lu +3 Lutetium 174.97 2-8-18-32-9-2

Actinide

89 Ac +3 Actinium (227) -18-32-18-9-2	90 Th +4 Thorium 232.04 -18-32-18-10-2	91 Pa +4 +5 Protactinium 231.04 -18-32-20-9-2	92 U +3 +4 +5 +6 Uranium 238.03 -18-32-21-9-2	93 Np +3 +4 +5 +6 Neptunium (237) -18-32-23-8-2	94 Pu +3 +4 +5 +6 Plutonium (244) -18-32-24-8-2	95 Am +3 +4 +5 +6 Americium (243) -18-32-25-8-2	96 Cm +3 Curium (247) -18-32-25-9-2	97 Bk +3 +4 Berkelium (247) -18-32-27-8-2	98 Cf +3 Californium (251) -18-32-28-8-2	99 Es Einsteinium (252) -18-32-29-8-2	100 Fm Fermium (257) -18-32-30-8-2	101 Md Mendelevium (258) -18-32-31-8-2	102 No Nobelium (259) -18-32-32-8-2	103 Lr Lawrencium (262) -18-32-32-9-2

PERIODIC TABLE OF THE ELEMENTS

14 ⟸ Group IUPAC
IVA ⟸ Group CAS
Atomic Number ⟹ 6
-4 +2 +4 ⟸ Selected Oxidation States
Symbol ⟹ C
Name ⟹ Carbon
12.011 ⟸ Atomic Mass
Electron Configuration ⟹ 2-4

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 +1 -1 **H** Hydrogen 1.0079 1																	2 0 **He** Helium 4.0026 2
2	3 +1 **Li** Lithium 6.941 2-1	4 +2 **Be** Beryllium 9.0122 2-2											5 +3 **B** Boron 10.811 2-3	6 -4 +2 +4 **C** Carbon 12.011 2-4	7 -3 -2 -1 +1 +2 +3 +4 +5 **N** Nitrogen 14.007 2-5	8 -2 **O** Oxygen 15.999 2-6	9 -1 **F** Fluorine 18.998 2-7	10 0 **Ne** Neon 20.179 2-8
3	11 +1 **Na** Sodium 22.990 2-8-1	12 +2 **Mg** Magnesium 24.305 2-8-2											13 +3 **Al** Aluminium 26.982 2-8-3	14 -4 +2 +4 **Si** Silicon 28.086 2-8-4	15 -3 +3 +5 **P** Phosphorus 30.974 2-8-5	16 -2 +4 +6 **S** Sulphur 32.065 2-8-6	17 -1 +1 +3 +5 +7 **Cl** Chlorine 35.453 2-8-7	18 0 **Ar** Argon 39.948 2-8-8
4	19 +1 **K** Potassium 39.098 2-8-8-1	20 +2 **Ca** Calcium 40.078 2-8-8-2	21 +3 **Sc** Scandium 44.956 2-8-9-2	22 +2 +3 +4 **Ti** Titanium 47.867 2-8-10-2	23 +2 +3 +4 +5 **V** Vanadium 50.942 2-8-11-2	24 +2 +3 +6 **Cr** Chromium 51.996 2-8-13-1	25 +2 +3 +4 +7 **Mn** Manganese 54.938 2-8-13-2	26 +2 +3 **Fe** Iron 55.845 2-8-14-2	27 +2 +3 **Co** Cobalt 58.933 2-8-15-2	28 +2 +3 **Ni** Nickel 58.693 2-8-16-2	29 +1 +2 **Cu** Copper 63.546 2-8-18-1	30 +2 **Zn** Zinc 65.39 2-8-18-2	31 +3 **Ga** Gallium 69.723 2-8-18-3	32 -4 +2 +4 **Ge** Germanium 72.64 2-8-18-4	33 -3 +3 +5 **As** Arsenic 74.922 2-8-18-5	34 -2 +2 +6 **Se** Selenium 78.96 2-8-18-6	35 -1 +1 +5 **Br** Bromine 79.904 2-8-18-7	36 0 +2 **Kr** Krypton 83.80 2-8-18-8
5	37 +1 **Rb** Rubidium 85.468 2-8-18-8-1	38 +2 **Sr** Strontium 87.62 2-8-18-8-2	39 +3 **Y** Yttrium 88.906 2-8-18-9-2	40 +4 **Zr** Zirconium 91.224 2-8-18-10-2	41 +3 +5 **Nb** Niobium 92.906 2-8-18-12-1	42 +3 +6 **Mo** Molybdenum 95.94 2-8-18-13-1	43 +4 +6 +7 **Tc** Technetium (98) 2-8-18-14-1	44 +3 **Ru** Ruthenium 101.07 2-8-18-15-1	45 +3 **Rh** Rhodium 102.91 2-8-18-16-1	46 +2 +4 **Pd** Palladium 106.42 2-8-18-18	47 +1 **Ag** Silver 107.87 2-8-18-18-1	48 +2 **Cd** Cadmium 112.41 2-8-18-18-2	49 +3 **In** Indium 114.82 2-8-18-18-3	50 +2 +4 **Sn** Tin 118.71 2-8-18-18-4	51 -3 +3 +5 **Sb** Antimony 121.76 2-8-18-18-5	52 -2 +4 +6 **Te** Tellurium 127.60 2-8-18-18-6	53 -1 +1 +5 +7 **I** Iodine 126.90 2-8-18-18-7	54 0 +2 +4 +6 **Xe** Xenon 131.29 2-8-18-18-8
6	55 +1 **Cs** Cesium 132.91 2-8-18-18-8-1	56 +2 **Ba** Barium 137.33 2-8-18-18-8-2	57-71 **La** Lanthanide	72 +4 **Hf** Hafnium 178.49 2-8-18-32-10-2	73 +5 **Ta** Tantalum 180.95 2-8-18-32-11-2	74 +6 **W** Tungsten 183.84 2-8-18-32-12-2	75 +4 +6 +7 **Re** Rhenium 186.21 2-8-18-32-13-2	76 +3 +4 **Os** Osmium 190.23 2-8-18-32-14-2	77 +3 +4 **Ir** Iridium 192.22 2-8-18-32-15-2	78 +2 +4 **Pt** Platinum 195.08 2-8-18-32-17-1	79 +1 +3 **Au** Gold 196.97 2-8-18-32-18-1	80 +1 +2 **Hg** Mercury 200.59 2-8-18-32-18-2	81 +1 +3 **Tl** Thallium 204.38 2-8-18-32-18-3	82 +2 +4 **Pb** Lead 207.2 2-8-18-32-18-4	83 +3 +5 **Bi** Bismuth 208.98 2-8-18-32-18-5	84 +2 +4 **Po** Polonium (209) 2-8-18-32-18-6	85 **At** Astatine (210) 2-8-18-32-18-7	86 0 **Rn** Radon (222) 2-8-18-32-18-8
7	87 +1 **Fr** Francium (223) -18-32-18-8-1	88 +2 **Ra** Radium (226) -18-32-15-8-2	89-103 **Ac** Actinide	104 **Rf** Rutherfordium (261) -18-32-32-10-2	105 **Db** Dubnium (262) -18-32-32-11-2	106 **Sg** Seaborgium (266) -18-32-32-12-2	107 **Bh** Bohrium (264) -18-32-32-13-2	108 **Hs** Hassium (277) -18-32-32-14-2	109 **Mt** Meitnerium (268) -18-32-32-15-2	110 +2 +4 **Uun** Ununnilium (281) -18-32-32-17-1	111 **Uuu** Unununium (272) -18-32-32-18-1	112 **Uub** Ununbium (285) -18-32-32-18-2	113 **Uut** Ununtrium (284)	114 **Uuq** Ununquadium (289)	115 **Uup** Ununpentium (288)	116 **Uuh** Ununhexium (291)	117 **Uus** Ununseptium	118 **Uuo** Ununoctium (294)

Electron Shells

1	K	2	S 2	P	D	F
2	L	8	2	6		
3	M	18	2	6	10	
4	N	32	2	6	10	14
5	O	32	2	6	10	14
6	P	18	2	6	10	
7	Q	8	2	6		
8	R	2	2			

Lanthanide

57 +3 **La** Lanthanium 138.91 2-8-18-18-9-2	58 +3 +4 **Ce** Cerium 140.12 2-8-18-20-8-2	59 +3 **Pr** Praseodymium 140.91 2-8-18-21-8-2	60 +3 **Nd** Neodymium 144.24 2-8-18-22-8-2	61 +3 **Pm** Promethium (145) 2-8-18-23-8-2	62 +2 +3 **Sm** Samarium 150.36 2-8-18-24-8-2	63 +2 +3 **Eu** Europium 151.96 2-8-18-25-8-2	64 +3 **Gd** Gadolinium 157.25 2-8-18-25-9-2	65 +3 **Tb** Terbium 158.93 2-8-18-27-8-2	66 +3 **Dy** Dysprosium 162.50 2-8-18-28-8-2	67 +3 **Ho** Holmium 164.93 2-8-18-29-8-2	68 +3 **Er** Erbium 167.26 2-8-18-30-8-2	69 +3 **Tm** Thulium 168.93 2-8-18-31-8-2	70 +2 +3 **Yb** Ytterbium 173.04 2-8-18-32-8-2	71 +3 **Lu** Lutetium 174.97 2-8-18-32-9-2

Actinide

89 +3 **Ac** Actinium (227) -18-32-18-9-2	90 +4 **Th** Thorium 232.04 -18-32-18-10-2	91 +4 +5 **Pa** Protactinium 231.04 -18-32-20-9-2	92 +3 +4 +5 +6 **U** Uranium 238.03 -18-32-21-9-2	93 +3 +4 +5 +6 **Np** Neptunium (237) -18-32-23-8-2	94 +3 +4 +5 +6 **Pu** Plutonium (244) -18-32-24-8-2	95 +3 +4 +5 +6 **Am** Americium (243) -18-32-25-8-2	96 +3 **Cm** Curium (247) -18-32-25-9-2	97 +3 +4 **Bk** Berkelium (247) -18-32-27-8-2	98 +3 **Cf** Californium (251) -18-32-28-8-2	99 **Es** Einsteinium (252) -18-32-29-8-2	100 **Fm** Fermium (257) -18-32-30-8-2	101 **Md** Mendelevium (258) -18-32-31-8-2	102 **No** Nobelium (259) -18-32-32-8-2	103 **Lr** Lawrencium (262) -18-32-32-9-2

Utah State Board of Education