CHAPTER 6 - BASIC CHEMISTRY

Since ancient times people have wanted to know what everything was made of. Some were just curious, but others known as alchemists wanted to find ways to change less valuable materials into more valuable ones such as gold.

Visual #6-1

Largely due to the influence of the famous philosopher Aristotle (384-322 BC), most ancient Greeks seem to have accepted the idea that everything on earth was made of four elements: earth, air, fire, and water, mixed in various proportions. The heavenly bodies were believed to be made of a fifth essence, the *quintessence*. He also said there were no such things as atoms.

We now know that Aristotle's ideas about matter were almost completely wrong. Though we can never be sure that we are 100% right, we can at least be sure that we are less wrong than he was.

Later in this chapter we will deal with how our present understanding of the atom and the periodic table developed over the centuries. For now, we will look at the kinds of practical considerations typically taught in an introductory chemistry class.

I. BASIC CONCEPTS OF PRACTICAL CHEMISTRY

Visual #6-2

Suppose you go to the grocery store and see a bag of bread that says, "Contains no chemicals." If you buy it, you are buying an empty bag. Everything, including your body, is made of chemicals. There are now 90 elements known to occur in nature and another 28 produced in laboratories, for a total of 118. Of these, every living thing known uses at least CHNOPS (carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus). In addition, living organisms use dozens of other elements. Mammals, for instance, also use calcium, magnesium, manganese, chlorine, and many others.

A. THERMODYNAMICS.

Scientific laws do not make anything happen, but simply describe what happens. The two best supported laws in all of science are the First and Second Laws of Thermodynamics.

1. First Law.

Visual #6-3

The First Law, also known as the **Law of Conservation of Matter and Energy**, refers to the *quantity* of energy. It says that energy cannot be created or destroyed by any known process. It can be converted back and forth, e.g., heat to electricity, electricity to light, and so on, but the total amount of matter and energy in the universe remains constant.

The First Law also includes the principle that matter and energy can be converted back and forth as described in the famous equation $e = mc^2$. Scientists have succeeded in converting matter into energy in nuclear reactions. There is no theoretical reason the process could not go the other way, though we have not yet converted energy to matter.

Since energy cannot be created by any known process, it had to come into existence either by an unknown *natural* process or an unknown *supernatural* process. Christians believe that since only God can create matter/energy, only He can create more or destroy what He already created. Gen. 2:1 tells us that His creative work is finished.

"Thus the heavens and the earth were finished, and all the host of them."

2. Second Law.

The Second Law, also known as the **Law of Entropy**, refers to the *quality* of energy. Though there are many ways to express this law, it means that energy tends to flow from greater to lesser concentration. In an *isolated* system (not subject to outside influences), the energy spreads outward. Since the sun and stars radiate a great deal of energy outward while receiving little or none from external sources, we could well wonder how the energy got into them in the first place.

A Big Bang is a poor explanation for the origin of the sun and stars. It would have produced an expanding cloud of matter and energy. If pockets within the expanding cloud reversed their expansion and came together trillions of trillions of times into high concentrations to produce stars, we would have to discard the Second Law – derived from observation – in favor of whatever unknown and unseen process was responsible.

Visual #6-4

Though we do not really have a good definition of energy, it is often described as the ability to produce change, that is, to do work. In order for work to be accomplished, there needs to be a difference in energy level from one location to another. For example, a steam engine works by converting chemical potential energy stored in some sort of combustible fuel into heat to boil water. The steam then moves other things attached to the engine. If there were no concentrated energy in the fuel, the water could not be heated and the engine would not operate.

The reason work can be accomplished is that the universe, stars, and earth still contain large concentrations of energy and are not yet at thermal equilibrium. The Second Law means that the universe is moving in that direction. Given enough time, all the energy in the universe will spread out and the universe will reach thermal equilibrium. The energy will still exist, but there will be no difference in energy levels between any two locations. No useful work will be possible and the universe will die a "heat death."

Visual #6-5

The Second Law is often expressed in terms of entropy, a measure of the disorganization or randomness of a system. Chemists recognize that the only types of chemical processes that are possible are those that increase the entropy of the universe, though they do not know why. The Bible tells us the reason:

Visual #6-6

"For the creation was subjected to futility, not willingly, but because of Him who subjected it in hope; because the creation itself also will be delivered from the bondage of corruption into the glorious liberty of the children of God. For we know that the whole creation groans and labors with birth pangs together until now." Romans 8:20-22 (NKJV)

3. **Entropy in open systems.**

Those who want to explain the universe by purely natural processes argue that the Second Law is irrelevant to the existence of God because there is no such thing as a completely isolated system. If atheistic evolution is correct this is false, because no influences could exist outside the universe itself. But what about systems which *are* subject to outside influences? In such cases a temporary reversal of the tendency toward increasing entropy is possible, but only under certain conditions.

a. **Supply of Usable Energy.**

Visual #6-7

There must be a supply of energy coming into the system from outside – not just any type of energy, but energy in a form usable by the system.

A baby is an example of an open system. He needs energy to grow, so we can give him plenty by setting off an atomic bomb next to him. He won't grow. It's the wrong kind of energy. He needs a specific type of energy available only in the form of food.

b. **Conversion Mechanism.**

Visual #6-8

There must be a mechanism to convert the supply of energy into a form usable by the relevant parts of the system. A baby can be surrounded by lobsters and steaks, but they won't do him any good because his digestive system is not yet mature enough to break them down into the proteins he needs. Until he develops a proper conversion mechanism, he has to drink milk. He even needs a conversion mechanism for that. Energy by itself isn't enough.

Visual #6-9

c. Pre-Existing Information.

There must be a preexisting source of information guiding the increase in organization. Even with food and a digestive system, a baby needs a building plan, DNA, put together new cell structures. Without DNA he will not grow. If he has defective DNA he will be deformed or dead.

Visual #6-10

d. Information vs. Order.

Some who want to explain everything by purely natural processes confuse information with order. They argue that order can increase spontaneously in crystalline structures such as ice. While this is true, the argument is irrelevant to the study of life.

In any chemical process, whether in an open or closed system, there is an interplay between energy (*enthalpy* -- the heat absorbed or released by the process) and entropy. Chemists use the equation

$$\Delta G = \Delta H - T\Delta S$$

to describe this interaction. (The Greek letter delta, Δ, is used to represent the difference between the before and after conditions of the reaction.) ΔG stands for the energy absorbed from or released to the universe, ΔH stands for the enthalpy change, T stands for the temperature in Kelvins, and ΔS stands for the entropy change. Only when ΔG is negative, that is, when energy is released to the universe, does a process occur spontaneously. This can happen under one of three conditions:

- If the process releases heat (the enthalpy change ΔH is negative) and the entropy increases because $T\,\Delta S$ is positive then both factors will be negative, giving a negative ΔG.
- If the process absorbs heat (the enthalpy change is positive) but the entropy due to $T\,\Delta S$ increases more than enough to offset it, then subtracting the larger $T\,\Delta S$ gives a negative result.
- If the entropy decreases ($T\,\Delta S$ is negative) but the process releases more than enough heat ΔH to offset it, then the more negative ΔH also gives a negative result.

The formation of ice is an example of the third set of circumstances. Though there is a decrease in the entropy of the water molecules as they link into crystals, the overall entropy of the universe increases as the molecules release energy in the form of heat.

Besides the release of heat, we also need to consider the role of information in the formation of ice. There is no more information in the solid vs. liquid states of water or any other substance that forms crystals. Using water as an example, the solid form (ice) is more orderly than the liquid form only because the molecules slow down enough to link together. However, the arrangement of the crystals is determined by the atomic structure of hydrogen and oxygen.

Water is not a straight molecule with an oxygen atom sandwiched between two hydrogens; instead, there are two unshared pairs of electrons on the oxygen atom that deform the molecule to about a 109° angle, somewhat like Mickey Mouse ears with oxygen (negative) as the head and the two hydrogens (positive) as the ears. Crystals do not form until the water molecules slow down enough for the positively charged hydrogen ends to link up with the negatively charged oxygen end of others nearby, but the potential for the crystalline structure is present even in the liquid and gaseous states. No information is added as they cool down to form ice crystals.

We can illustrate the difference between order and information as follows.

Suppose we take a random assortment of 113 letters:

Visual #6-11

VTERABUTSHEOLHGFOEHNWYTEHTSVDHEAONTIEVHL
STEHIDVOAVLDEHTUOIORSPEGELORSBOHILEDOERTO
NATBOELIMSOEAFRLINSTHENGNIHTVEGW

If we put them in alphabetical order it comes out like this:

Visual #6-12

AAAAA BBB DDDD EEEEEEEEEEEEEEEEFF GGGG
HHHHHHHHHHH IIIIIII LLLLLLL M NNNNNN OOOOOOOOOOOO
P RRRRR SSSSSSS TTTTTTTTTTT UU VVVVVV WW Y

It may be orderly, but it doesn't mean anything. However, when these same letters are arranged in a specific way, they say

Visual #6-13

FOR GOD SO LOVED THE WORLD THAT HE GAVE HIS
ONLY BEGOTTEN SON THAT WHOSOEVER BELIEVETH IN
HIM SHOULD NOT PERISH BUT HAVE EVERLASTING LIFE.

This arrangement contains not just order but information.

In order for a collection of matter and energy to form a living cell with all its complex parts, it must contain not just order but a vast amount of information. The information determines the specific pattern in which the cell's atoms are arranged into amino acids, proteins, DNA, and the like. This kind of specified complexity is exactly the opposite of what happens when chemicals are left to themselves.

e. **Entropy Increase at the Energy Source.**

Visual #6-14

Any open system is part of a larger system that also includes the energy supply. In order for entropy to decrease in the smaller system, it has to increase at least as much at the energy source. For example, a teenager uses a hamburger as fuel for growth. The hamburger came from a cow that ate plants that grew by getting energy from the sun. The plant, cow, and teenager temporarily decrease in entropy as they grow, but the sun's entropy increases at least as much as theirs decrease. There is always a cost.

There is not a single documented case of either an open or closed system spontaneously increasing in organization apart from these conditions.

Remember, atheists argue that living things are open systems and thus immune to the Second Law of Thermodynamics. While the term "Second Law" applies specifically to closed systems, the tendency toward increasing entropy applies to living cells as well as everything else.

- Entropy allows simple components of cells such as amino acids to come together spontaneously because they are thermodynamically favorable. (ΔG is negative in the aforementioned equation $\Delta G = \Delta H - T\,\Delta S$.)
- The more complex components such as proteins and DNA are thermodynamically very *un*favorable. Entropy prevents them from coming together apart from the conditions described above.

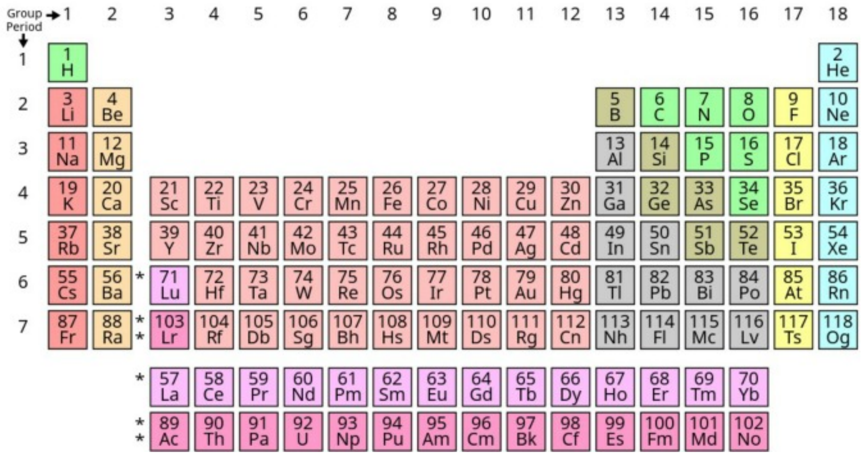
Because living cells are open systems that meet all the conditions described above, they can decrease in entropy for a while. Nevertheless, since they consist of matter and energy far out of equilibrium with their surroundings, they eventually fall prey to entropy. They die, causing thermodynamically unfavorable reactions to stop abruptly. The tendency toward increasing entropy takes over and they begin to decay into simpler, more thermodynamically favorable substances. It's a one-way process.

B. ELEMENTS, COMPOUNDS, AND MIXTURES.

The distinction between elements, compounds, and mixtures lies in how they can be separated into simpler materials.

- An element cannot be separated into simpler materials by anything short of a nuclear process that changes it into a different element.

Visual #6-15



File URL: https://commons.wikimedia.org/wiki/File:Simple_Periodic_Table_Chart-en.svg

Attribution: Released into Public Domain by creator Offnfopt, via Wikimedia Commons

Visual #6-16

- A compound consists of two or more elements combined in a fixed ratio. Its properties are almost always different from the properties of the elements of which it is composed. For instance, table salt is composed of the elements *sodium* (a metal that reacts explosively with water) and *chlorine* (a green, poisonous gas). Yet when the two come together to form a compound you eat it on your food.

    A compound can only be separated into its components by chemical means such as the addition of acids or electricity. (Electricity is considered a chemical means because atoms are held together by electrons.) If the formula changes, it becomes a different compound.

Visual #6-17

- Almost everything else is a mixture. A mixture is a collection of elements and compounds without a definite formula, such as mud, salt water, or coffee.

    A mixture may be *homogeneous* or *heterogeneous.* Salt water is an example of the former because it looks the same everywhere even when viewed through a microscope. Mud or concrete are heterogeneous mixtures because they have visible differences.

    A mixture of solids or liquids can be separated by physical means such as sifting, boiling, using magnets, putting it in a centrifuge, and so on. A mixture of gases can be separated by cooling in a process called fractional distillation. Each gas turns into a liquid at a different (very cold) temperature. As a mixture of gases such as air is cooled, the components liquefy one by one and can be separated from those that are still in the gaseous state.

C. ATOMS, MOLECULES, AND FORMULA UNITS.

Since an atom is so small, we cannot directly see the details. However, we can use a technique called X-ray crystallography to get a blurred image of the shapes of molecules.

1. Atoms.

Visual #6-18

An atom is the smallest particle of an element that retains all the chemical properties of that element. Though at a quantum mechanical level the details are far more complicated than will be discussed here, for the purposes of practical chemistry an atom is made of negatively charged electrons, positively charged protons, and neutrons with no electrical charge.

- Electrons are the lightest particles and occupy the space around the center, or nucleus.

- Protons and neutrons are in the nucleus of the atom. Protons have about 1836 times as much mass as electrons, neutrons 1837.

2. **Molecules.**

Visual #6-19

A molecule is a complete, self-contained unit with a definite boundary.

Most molecules can be defined as the smallest particles of a compound that retain all the properties of the compound. For instance, a water molecule has the formula H_2O. If we separate it into its components hydrogen and oxygen, it is no longer water.

There are seven exceptions to the general rule that molecules represent **compounds**. Though almost all of the of the elements on the periodic table can exist as single atoms, seven elements are not known to exist as single atoms but as *diatomic* molecules of two atoms each. The seven diatomic elements are Hydrogen, Nitrogen, Oxygen, Fluorine, Chlorine, Bromine, and Iodine. Unless they are part of a compound, they link with another atom like themselves and occur in the form H_2, N_2, O_2, F_2, Cl_2, Br_2, and I_2.

This does not mean that there can only be one atom of a diatomic element in a compound. For instance, oxygen in its elemental form is O_2, but a compound such as water (H_2O) does not have to have two oxygen atoms.

3. **Formula units.**

Visual #6-20

Many compounds such as table salt (NaCl) do not consist of individual, self-contained molecules. Instead, they consist of alternating positive and negative ions going in three dimensions with no theoretical limit to the number of each. For such compounds, the *formula unit* shows the simplest ratio of positive and negative ions. This type of compound forms crystals rather than molecules.

D. SUBSTANCES VS. MIXTURES.

In ordinary conversation, we often use the words “substance” and “material” interchange-ably. This is not the case in chemistry. A substance has a definite formula, whereas a material can be any sort of “stuff.”

- A substance can be an element whose formula is its symbol on the Periodic Table.
- A substance can also be a compound with a fixed formula such as H_2O, CO_2, or $C_{12}H_{22}O_{11}$ (sugar). There are tens of thousands of compounds known.
- Every other type of material (air, mud, sea water, coffee, the human body) is a mixture. If there is no definite chemical formula then it is a mixture.

E. PHYSICAL AND CHEMICAL PROPERTIES.

Visual #6-21

- Physical properties can be detected by simply **observing** the material. They include color, shape, size, hardness, state, taste, smell, and do on.
- Chemical properties have to do with how a material reacts or does not react. They can only be detected by doing experiments that at least try to change the chemical formula. Failure to react (no change of formula) is also a chemical property.

F. PHYSICAL AND CHEMICAL CHANGES.

- Physical changes only change the physical properties of the material. It may look different, get hotter or colder, change from one state of matter to another and so forth, but its chemical formula does not change.
- Chemical changes automatically involve a change of formula and thus a change of chemical properties.

G. STATES OF MATTER.

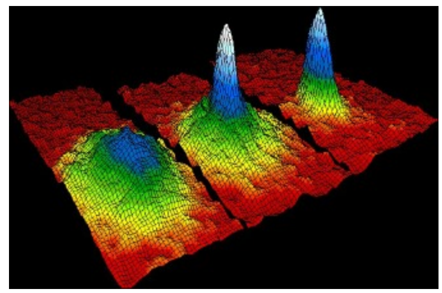
Visual #6-22

According to the Kinetic Theory of Matter, atoms are constantly moving. The state or *phase* of matter depends upon how fast they move as well as other factors such as arrangement of electrons.

1. **Solids.** In a solid, the particles are moving slow enough to link up with each other. A solid has a definite volume and shape.

2. **Liquids.** In a liquid, the particles are moving a bit faster so that they are not locked in with each other, but there is still enough attraction that they slide past each other rather than go flying off into the air. Liquids have a definite volume but take the shape of their container.
3. **Gases.** In a gas, the attraction of the particles is weak enough that they can break free and go flying away. A gas in a container takes the volume and shape of the container.
4. **Plasma.** If a material receives so much energy that it loses some or all of its electrons, it changes into a higher energy state known as a plasma. Because stars are made of plasma, it is believed to be the most common state of matter in the universe. Plasma takes the size and shape of its container.
5. **Bose-Einstein Condensate (BEC).** In the 1920s Indian physicist Satyendra Bose predicted that if a material were brought to a temperature very close to absolute zero (zero on the Kelvin scale, -273.15° C), its particulate nature would disappear and it would manifest itself as waves. Einstein was impressed and collaborated with Bose to predict the existence of a fifth state of matter, a Bose-Einstein Condensate. The first BEC was created in a lab in 1995 (for which the creator received a Nobel Prize). Several others have been produced since then. (Since it requires conditions close to absolute zero, very few people will ever actually see a BEC.)

Visual #6-23



https://commons.wikimedia.org/wiki/File:Bose_Einstein_condensate.png: National Institute of Standards & Technology/JILA/CU-Boulder, Public domain, via Wikimedia Commons

6. **Quark Soup.** Yet another state of matter has been proposed: "Quark Soup," or quark-gluon plasma. This would occur at energies so high that protons and neutrons break down into even simpler particles called quarks. Quark soup is believed to have been formed several times in supercolliders, but the results have been so unstable that they persisted for only a fraction of a second.

H. THE PERIODIC TABLE.

Visual #6-24

Visual #6-25

About 90 elements are known to exist in nature. Others have been artificially produced in laboratories, for a total of 118. The elements are arranged on the Periodic Table (see next page) in vertical columns (*groups*) and horizontal rows (*periods*). Each has a unique one or two letter chemical symbol. The symbol is related to the name, though some of the symbols came from Latin. For instance, Sodium (Na) in Latin was Natrum, Lead (Pb) was Plumbum, and Potassium (K) was Kalium.

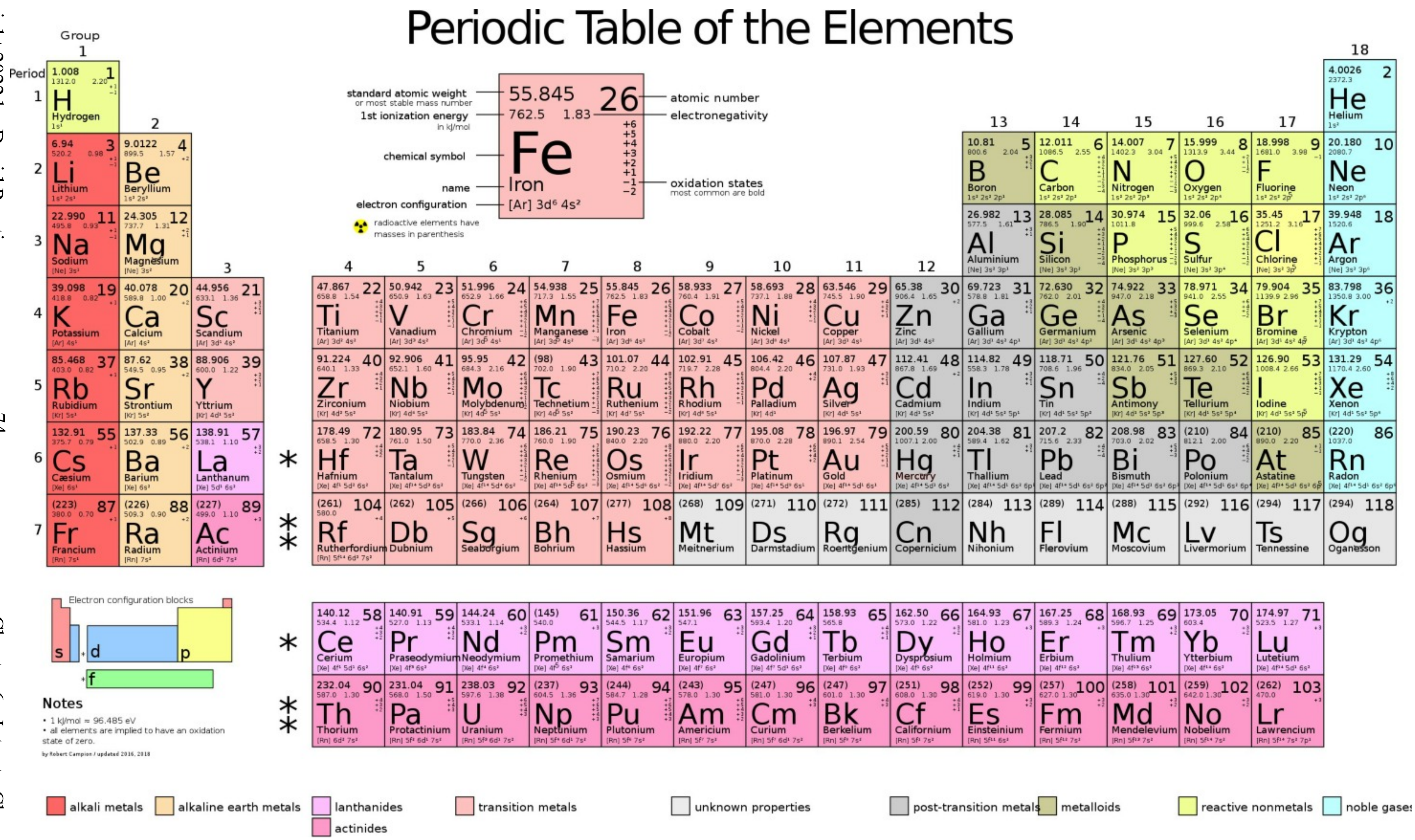
The two rows going across the bottom actually belong in Periods 6 and 7, after Lanthanum (atomic # 57) and Actinium (#89). They are placed at the bottom so that the periodic table will fit on a standard size sheet of paper.

1. **Regions on the periodic table.**
   - Most of the elements on the periodic table are *metals*. They tend to give up electrons easily and are usually good conductors of electricity.
   - Those on the right side are *nonmetals*. The noble gases in the last group do not react unless forced to. The other nonmetals usually try to gain electrons and are not good conductors of electricity.

Visual #6-26

   - The elements along the stair step line going diagonally from Group 13 to Group 18 are *metalloids* and have some characteristics of both metals and nonmetals. Because their conductivity can be controlled, they are very useful in electronic technology.

COURTESY OF WIKIMEDIA USER 2012RC



Periodic Table compiled by WIKIMedia User 2012rc. Page URL: https://commons.wikimedia.org/wiki/File:Periodic_table_large.svg

2. Relative strength in attracting electrons.

- A neutral atom has the same number of electrons as it has protons. When atoms gain or lose electrons they become *ions* with either a positive or negative electric charge. We can predict whether they will become positive or negative by consulting a table of *electronegativity*. This is the tendency of atoms to attract electrons when in an chemical compound, rated on a scale of zero to four.

  Elements on the left end of the periodic table tend to have lower electronegativity. They give up their electrons to other atoms more easily than those on the right. When they release electrons, they form positively charged particles called *cations* (pronounced cat-ions).
- Those on the right have higher electronegativity and tend to attract the electrons more strongly. When they gain electrons, they may become negative ions called *anions* (pronounced ann-ions).
- When two elements are similar in electronegativity, neither is able to take away the other's electrons. In this case, they tend to share them.
- Electronegativity is usually not shown for the noble gases because they do not get into chemical reactions unless they are forced to under extreme circumstances.

II. CHEMICAL REACTIONS.

Visual #6-27

The parts of an atom most relevant to chemical processes are the protons, neutrons, and electrons. (Smaller parts such as quarks do not have many practical effects.) Though the protons and neutrons have their own functions, the electrons allow atoms to combine and separate in a great many ways.

A. FUNCTION OF THE SUBATOMIC PARTICLES.

- The atom has a positively charged *nucleus*. The positive charge comes from the *protons*. The number of protons is known as the *atomic number*. From the perspective of chemical reactions, the main function of protons is to attract electrons.
- The nucleus also contains *neutrons*. If two or more positively charged particles are placed close together, they repel each other and try to fly apart. Scientists do not know why protons do not do so, but have named whatever force keeps them together the "Strong Nuclear Force."

> The Bible mentions this force:
>
> For by him all things were created, in heaven and on earth, visible and invisible, whether thrones or dominions or rulers or authorities—all things were created through him and for him. And he is before all things, and in him all things hold together. (Col. 1:16-17 ESV)
>
> Jesus not only created the universe but also furnishes the force that holds together the protons in atoms.

  We do not know how, but neutrons are somehow involved in the strong nuclear force. In general, if there are between one to 1 ½ times as many neutrons as protons in a nucleus, it will stay together with varying degrees of stability. From the perspective of chemical reactions, the main function of neutrons is to keep protons together so they can attract the tight number of electrons.
- The number of protons and neutrons added together is the *mass number* of the atom. This is also known as the *isotope* number. Isotopes of the same element have the same number of protons but different numbers of neutrons.
- The *atomic mass* as shown on the periodic is the weighted average of all the isotopes of the elements – that is, it takes into account not only the mass number of each isotope, but how many there are of each.

- Electrons do almost everything else. Their attraction to the protons in the nuclei of their host atoms as well as others nearby is responsible for every chemical reaction.

B. USING THE PERIODIC TABLE TO PREDICT REACTIONS.

The history of the periodic table will be discussed later in this chapter.

The latest version (see two pages previous) as approved by the International Union of Pure and Applied Chemistry (IUPAC) has seven horizontal rows known as *periods*, 18 vertical columns or *groups* labeled 1 - 18, and a block at the bottom that is fourteen spaces wide and two spaces high. This block (the inner transition metals) actually belongs between groups three and four in periods six and seven, but it is usually placed underneath to prevent the table from being too wide to fit on a printed page.

1. Shells (Principal energy levels).

Visual #6-28

The arrangement of electrons around the nuclei of the atoms is much more complicated than space allows us to describe in this course. In general, the first period (first principal energy level) can contain up to two electrons. The second and third periods can each contain up to eight. The fourth and fifth can each contain up 18. The sixth and seventh can each contain up to 32. No one knows why these are the numbers for each period, so 2, 8, 8, 18, 18, 32, and 32 are commonly called the "magic numbers" by chemists.

> This course is intended to give an extremely simplified presentation. Besides the principal energy levels, there are also many sublevels. However, the sublevels are less involved in allowing us to predict chemical reactions than the principal levels are.

We often use the way the shells on an onion are arranged to illustrate the arrangement of electrons. The more shells there are, the larger the atom. The electrons in the inner shells have little or no influence on chemical reactions.

2. Valence electrons.

A periodic chart that shows electronegativity such as the one two pages previous makes it much easier to predict how atoms will combine into compounds.

Visual #6-29

The electrons most involved in reactions are the *valence* electrons in the outer shell. For some unknown reason, most atoms become most stable when they have eight valence electrons. (The exceptions are the first five elements H, He, Li, Be, and B, which do not have enough protons to attract eight electrons. They are most stable when they have two valence electrons.)

- The elements in Group 1 have one valence electron each. With the exception of Hydrogen, they are all metals and tend to release this single valence electron easily. Once they lose the one outer electron, its shell is gone. The next shell inward has eight electrons, making it very stable. As a result, of giving up one electron, Group 1 elements usually form ions with a 1+ charge. (Chemists usually put the plus and minus after the number, not before.)

  Hydrogen holds to its valence electron more tightly than the metals in its group. It tends to share its electron rather than giving it away.
- Group two elements have two valence electrons. They tend to give them away fairly easily in chemical compounds, leaving the next inward shell very stable with eight electrons. They usually form ions with a 2+ charge.
- Groups 3 through 12 are much less predictable. The inner shells are close in energy to those in the valence shell, so sometimes electrons in those shells act like valence electrons. Once the atoms react, they have a complete outer shell of eight electrons.
- Group 13 has three valence electrons. Atoms in this group tend to release three electrons to leave the next inward shell complete. The ions usually have a 3+ charge.
- Group 14 is a mixed group. Some elements have characteristics of metals, others

metalloids, and the rest nonmetals. Their electronegativity is a bit higher, indicating that they tend to share their valence electrons rather than releasing them. Once they acquire enough shared electrons to have eight in the outer shell, they become stable.

Carbon is especially important to living things, because it is the only element known that can form the long chains necessary to make proteins and DNA.

- Groups 15, 16, and 17 have 5, 6, and 7 valence electrons respectively. They are mostly nonmetals. The elements along the bottom in Period 7 are known only in artificially produced form, so few people will ever encounter them.

  The common elements in these groups tend to have high electronegativity and hold their electrons strongly. If they are close to atoms with much lower electronegativity, they tend to take the valence electrons away from those atoms. In this case, Group 15 elements form 3- ions, Group 16 form 2-, and Group 17 form 1-.
- Noble gases (Group 18) do not react and do not form ions except under extraordinary conditions in the laboratory.

3. Ionic, Covalent, and Polar Covalent Bonds.

Visual #6-30

If an atom with very low electronegativity (left side of the periodic table) encounters one with a high electronegativity (right side), it tends to lose its electron(s) while the one on the right tends to take them away. However, if the two elements are very close in electronegativity, they tend to share whatever number are necessary for each atom to be surrounded by eight valence electrons. If the electronegativities are close, the electrons will be shared evenly. If there is a fair amount of difference in electronegativity, the one with a higher value pulls the electrons more closely to itself, but the other one does not let go completely. This is called a polar covalent bond.

In general, if the difference in electronegativity between two atoms is 1.7 or higher, the bond will be ionic. If the difference is between about 0.4 and 1.7, the bond is polar covalent. If the difference is between 0 and 0.4, the bond is considered pure covalent.

4. Chemical formulas.

The formula of any compound is written by using the symbol of each element from the periodic table followed by a subscript indicating how many atoms there are, then the same information for the next element, until all the elements and their quantities have been listed. For instance, water is H_2O, sulfuric acid is H_2SO_4, and sucrose (table sugar) is $C_{12}H_{22}O_{11}$.

5. Polyatomic ions.

Visual #6-31

Many ions are composed not just of one element but of several atoms covalently bonded together. These are called polyatomic ions and function as a single unit. There are many types of polyatomic ions. Some of the more common ones are NO^{3-} (nitrate), SO 4 $^{2-}$ (sulfate), OH^- (hydroxide), NH_4^+ (ammonium), CO_3^{2-} (carbonate), and $C_2H_3O_2^-$ (acetate).

If a compound contains more than one of the same polyatomic ion, its formula is placed in parentheses with an appropriate subscript. For example, aluminum sulfate has a formula of $Al_2(SO_4)_3$.

C. CHEMICAL EQUATIONS.

The way chemicals react is written with one or more substances on the left side of an arrow (reactants), an arrow indicating that a reaction takes place (*yields*), and one or more substances on the right (products). Though it is called an equation, there is no equal sign.

In order to *balance* the equation to ensure that the same number of atoms of each element are present on both sides, coefficients indicating the number of molecules or formula units may be necessary.

Several of the more familiar types of reactions:

Visual #6-32

$2H_2 + O_2 \rightarrow 2H_2O$	Synthesis or combination
$CaCo3 \rightarrow CaO + CO_2$	Decomposition
$Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$	Single replacement/displacement
$CaCl_2 + Na_2SO_4 \rightarrow CaSO_4 + 2NaCl$	Double replacement/displacement
$C_{10}H_8 + 12\ O_2 \rightarrow 10\ CO_2 + 4\ H_2O$	Complete combustion
$C_2H_5OH + 2O_2 \rightarrow 2CO + 3H_2\ O$	Incomplete combustion

There are also many other types involving acids, bases, neutralization, and so on.

- Symbols may be placed above the arrow to indicate the need for heat (Δ), light, electricity, catalysts to speed up the reaction, and so on.
- The state of matter (s, l, g) is often indicated.
- An up arrow (↑) indicates that a gas appeared, and a down arrow (↓) indicates that a precipitate (solid) was formed).
- A double headed arrow (↔) indicates that a reaction is reversible.

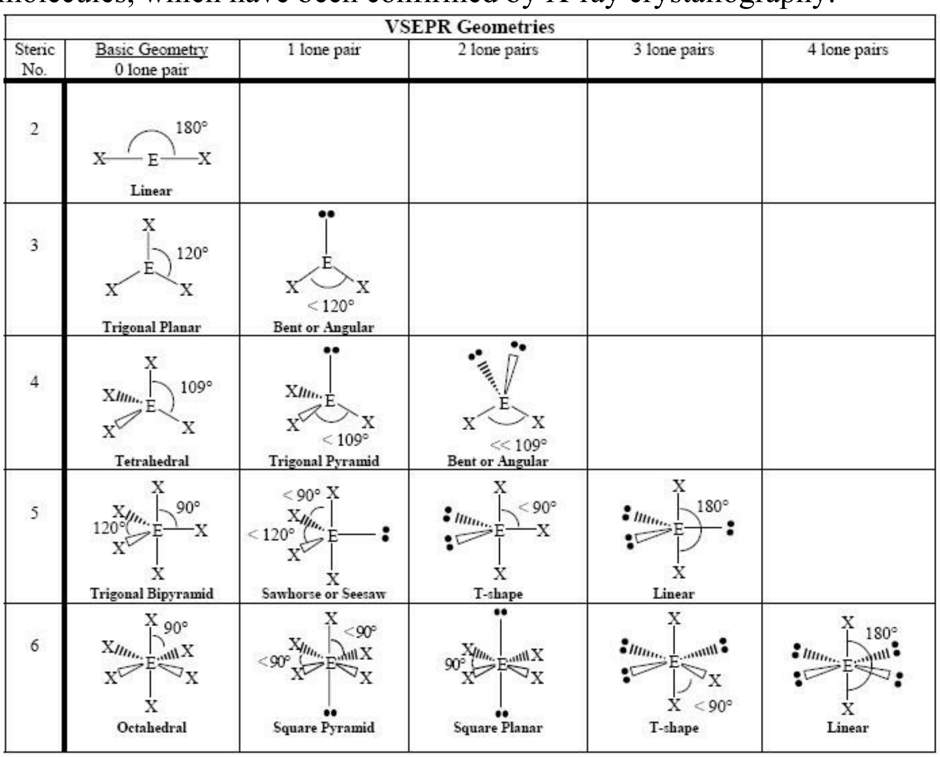
D. 3 DIMENSIONAL SHAPES OF MOLECULES.

Visual #6-33

Many molecules have three dimensional shapes because of the arrangement of valence electrons around the atoms in the center of the molecule. This arrangement may be crucially important when the central atom is carbon, the basic element needed for life. All proteins use only certain shapes of carbon compounds, as do the nucleic acids DNA and RNA.

A molecule of two atoms is automatically linear. One with three atoms may be linear or triangular (trigonal planar). One with four may be tetrahedral or pyramidal. Other shapes include trigonal bipyramidal, octahedral, square planar, and many others.

The well supported Valence Shell Electron Pair Repulsion (VSEPR) Theory says that valence shell electrons work in pairs. The theory predicted the following shapes for molecules, which have been confirmed by X-ray crystallography.



Molecular shapes courtesy of Dr. Regina Frey.

https://commons.wikimedia.org/wiki/File:VSEPR_geometries.PNG Placed in public domain by Dr. Regina Frey, Washington University in St. Louis, via Wikimedia Commons

A medicine such as thalidomide with one shape may be perfectly safe while a medicine with the same formula but a different shape may cause birth defects, as tragically occurred in the early 1960s.

These are just a few of the important topics in chemistry. Others such as acids, bases, pH, and organic chemistry are not even mentioned because it is not possible in a brief introductory course such as this to cover them all. Many resources are available to help serious students learn more.

III. HISTORICAL DEVELOPMENT OF CHEMISTRY.

Though some self-identified atheists try to make it seem as if belief in God or the Bible are somehow anti-science, many of the great discoveries in chemistry have been made by scientists who identified themselves as Christians: Boyle. Lavoisier, Faraday, Maxwell, Compton, Newton, Dalton, Gauss, J.J. Thomson, Volta, Pascal, Lord Kelvin, Heisenberg, Davy, and Eddington to name just a few.

A. THE DEMOCRITUS ATOM.

Visual #6-34

At least one of the ancient Greeks, Democritus (460-370 BC), was not willing to accept the prevailing wisdom regarding the structure of matter. He recognized that if you cut something like a block of gold in half it would still be gold. If you cut it again it would still be gold. However, he reasoned that if you cut it in half enough times, it would reach a level where it could not be cut any more. Since the Greek word for "cut" was "*tom*" (as in Computer *Tomography*, in which objects are virtually cut apart), this would be the "not cuttable" level, *atomos*, from which we get the word atom.

Some of the ideas Democritus proposed were:

1. Everything is made of atoms.
   There would have to be an infinite number of atoms to make up all material objects.
2. All atoms of the same element have the same shape.
   Atoms of *different* elements were not necessarily all the same shape. Their differences in taste, degrees of hardness, and so on were because of different shapes.
3. Atoms cannot be destroyed.
4. Atoms are surrounded by empty space.
5. Atoms are always in motion.

His ideas did not come from experimentation, but simply from reasoning. When Aristotle (384-322 BC) came to prominence just a few years later, he said that Democritus had to be wrong because there could not be any such thing as empty space. Because of Aristotle's prestige, the idea of atoms was discarded for almost two thousand years.

B. CONTRIBUTIONS OF ALCHEMISTS.

Visual #6-35

Meanwhile, not everyone agreed with Aristotle that everything on earth was made out of only four elements. Various types of metals such as iron, copper, lead, gold, and silver had been known and used since even before his time, though no one knew what they were made of. People in other parts of the world not influenced by the Greeks, e.g., South America and India, developed techniques to extract and refine materials from raw ores in the ground. Carbon, sulfur, and other metals were discovered over the centuries, especially by alchemists looking for a cheap way to turn other materials into gold.

The alchemists did not contribute significantly to atomic theory, but they developed equipment and techniques still in use today. For instance the mortar and pestle and the crucible used in labs have not changed in thousands of years. The glassware they designed is the pattern for much of what is used today. They also developed techniques for separating materials into their components, which are still the basis of much of analytical chemistry.

C. LAVOISIER.

Antoine Lavoisier (1743-1794) is considered one of the fathers of experimental chemistry. By his time, about 33 elements had been identified.

- He demonstrated the Law of Conservation of Mass by doing experiments in sealed

containers that showed that if nothing was allowed to escape, the mass after the reaction was the same as the mass before.
- Though at first he mistakenly included light and heat (*phlogiston*) among the elements, he later realized that reactions with an unknown element in the atmosphere were responsible for many of the reactions that released heat. Lavoisier's contemporary Joseph Priestley (1733-1804) had done experiments on the subject. When Lavoisier was successful in repeating those experiments, he named the previously unknown gas oxygen.
- He invented a lens allowing him to obtain higher temperatures than in a furnace.
- He was also instrumental in developing the system of nomenclature still used in modern chemistry.

Lavoisier's career was literally cut short by the French Revolution. As a member of the aristocracy, he was guillotined during the "Reign of Terror" in 1794. A scientist to the end, he told his contemporaries that he would blink for as long as possible to let them know if there was still consciousness after beheading. Some reports said that he blinked for up to 30 seconds.

D. DALTON.

Visual #6-36

John Dalton (1766-1844) was a faithful member of the Christian sect called Quakers. Though he was a schoolteacher rather than a chemist, he is considered the founder of the modern atomic theory.

Despite the fact that it had been many years since the world of chemistry paid much attention to Democritus' ideas, Dalton found a way to test them at least indirectly. In 1794, his contemporary Joseph-Louis Proust (1754-1826) published the Law of Definite Composition, also known as the Law of Definite Proportion. It was based on observations that any time chemists performed chemical reactions, there was an optimum ratio between the reactants that would produce almost entirely products with almost no reactants left over. Dalton used this idea to form the hypothesis that there must be an ideal ratio of atoms of each element in the formation of a compound. Unlike the ideas of Democritus, Dalton's could be tested. He published his new theory in 1808 in *A New System of Chemical Philosophy.*

The main features of Dalton's Atomic Theory were:

1. All matter is made of indivisible atoms.
2. All atoms of a given element are identical to each other.
3. Two or more atoms can combine in various ways to make compounds.
   The atoms in a compound will combine in simple whole-number ratios.
   The properties of the compound may be very different from the properties of the component elements.
4. Chemical reactions occur as a result of atoms being rearranged.

Visual #6-37

In order to qualify as a scientific theory, a hypothesis has to have the potential to be falsified. Two of Dalton's points were later falsified: (1) The atom can be subdivided into parts, though those parts no longer have the properties of the original element, and (2) Not all atoms of the same element are identical, but can exist in different forms called *isotopes*. However, the theory was powerful enough that it did not have to be thrown out, just modified.

Dalton added to the knowledge of gases with his Law of Partial Pressures. He realized that air was not a single element but a mixture of gases including the element oxygen discovered a few years earlier by Lavoisier. He formulated the Law of Partial Pressures, which says that each individual gas furnishes a partial pressure that contributes to the whole.

Shortly after Dalton published his Atomic Theory, the Italian physicist Amedeo Avogadro (1776-1856) proposed that equal volumes of different gases at the same temperature should have the same number of molecules. This hypothesis, along with a comparison of the masses of different gases in containers of equal volume, led to concept of relative atomic weights of the elements in 1811. This would later become a key feature in the development of the Periodic Table.

> In physics, weight and mass are two different things entirely. In chemistry, atomic mass and atomic weight are treated as synonymous.

E. MENDELEEV AND THE PERIODIC TABLE.

Visual #6-38

Dmitri Mendeleev (1834-1907) was another schoolteacher who became a chemist. He did not concern himself with questions about the the structure of the atom, but instead wanted to know what elements existed.

By 1869, about 63 elements were known. Mendeleev decided to make cards showing their properties and arrange them on a table according to the atomic weights calculated by earlier chemists such as the Swedish Jöns Jacob Berzelius (1779-1848). (Melhado, 2022)

> Berzelius is a little known chemist who made major contributions to chemistry. In 1800, the Italian physicist and chemist Alessandro Volta, a devout Catholic (not to be confused with the atheist Voltaire) invented the first battery, known as a voltaic pile. Berzelius took advantage of the invention to separate compounds into their components. He determined that compounds were made of some parts that were more positive and others that were more negative. He also invented the names "isomer" and "catalyst."
>
> Using Avogadro's aforementioned principle that different gases at the same volume had the same number of atoms, scientists such as Berzelius had been able to compare their relative masses. Hydrogen, the lightest gas, was assigned a relative mass of one. Other gases were assigned relative masses as compared to it. Then, using the atomic masses of the two most active gases (oxygen and fluorine) and reacting them with solid or liquid elements, he was able to determine the masses of the products and thereby the relative masses of many of the solid elements. (Melhado, 1998; "Jacob Berzelius," 2017.)

When Mendeleev arranged the elements by atomic weight, he found that their chemical properties repeated periodically. He started new rows so that the vertical columns (groups) would have similar properties. He left blanks for unknown elements that he correctly believed would be discovered later.

Meanwhile, the German (Julius) Lothar Meyer was working on his own version of a periodic table. However, Mendeleev published his work first and also made predictions about missing elements, most of which turned out to be correct. Meyer did not make such predictions, so his work faded into obscurity.

Many more elements have been discovered or manufactured since Mendeleev's time. The periodic table has had to be modified, but it is still recognizable as the basic design he came up with.

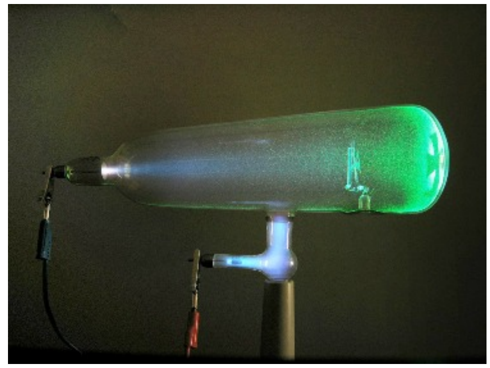
F. THOMSON AND THE DISCOVERY OF THE ELECTRON.

By the late 1800s Dalton's idea that the atom could not be broken down into smaller parts had gained widespread acceptance. However, this idea was soon to be falsified.

Visual #6-39

Volta's invention of the battery (first known as a *voltaic pile*) made it much easier to perform experiments involving electricity. By putting batteries in series, scientists could obtain as high a voltage as they needed. One of those who did such work with electricity was the famous English physicist Michael Faraday (1791-1867). Out of curiosity, he decided to run a high voltage electric current between two electrodes inside a glass tube. As he pumped out more and more of the gases inside the tube, a glow began to travel from the negative terminal (the *cathode*) to the positive (the *anode*).

Others repeated his experiments and found that the best results were obtained with very low gas pressure, but not a complete vacuum. One of the scientists whose cathode ray tube design worked the best was Sir William Crookes (1832 – 1919), for whom the Crookes tube was named. He discovered that the glow bent in response to a magnet. This meant that it was not pure energy. Though a very strong magnetic field can distort the medium through which energy travels, the magnets used were not particularly strong. The bending indicated that whatever was producing the glow consisted of charged particles of matter. Crookes and others also noticed that the results were the same no matter what gas was used in the tube. This would indicate that whatever the particles were, they were present in all the atoms tested.

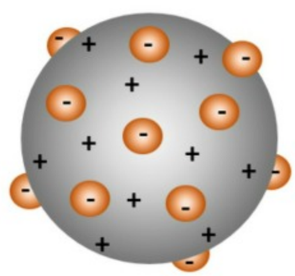


Crookes Tube
https://commons.wikimedia.org/wiki/File:Crookes_tube-in_use-lateral_view-standing_cross_prPNr%C2%B011.jpg
Attrribution: D-Kuru, CC BY-SA 2.0 AT <https://creativecommons.org/licenses/by-sa/2.0/at/deed.en>, via Wikimedia Commons

J.J. Thomson (1856-1940) held the prestigious title of Cavendish Professor at Trinity College, Cambridge (Isaac Newton's alma mater). Thomson was not the first one to study the behavior of cathode rays, but he was the first to calculate the ratio of charge to mass for the newly discovered subatomic particles of which they were composed. He did this by placing positively and negatively charged plates above and below the beam to see how much it would deflect when different voltages were applied. When he received the Nobel Prize for this discovery in 1906 he called the particles *corpuscles*, though they later came to be known as electrons.

It was now firmly established that Dalton had been wrong and that the atom could be broken down into smaller particles. The question naturally arose: *Where were the electrons when they were not flowing?* Thomson proposed the "Plum Pudding Model" in which the atom was more or less a lump of positive charge with electrons embedded throughout it when not flowing. ("J. J. Thomson Autobiography," 2013.) To those not familiar with plum pudding, it would make more sense to call it the "chocolate chip cookie" model.

Joseph J. Thomson
(1856-1940)



https://commons.wikimedia.org/wiki/File:Modelo_at%C3%B3mico_de_Thomson_2021.png
Released into public domain by Valkurare, CC0, via Wikimedia Commons

> Robert Millikan (1868-1953) later did an experiment involving oil droplets that allowed him to calculate not just the charge to mass ratio, but the actual mass of the electron. He received the Nobel Prize in 1923.

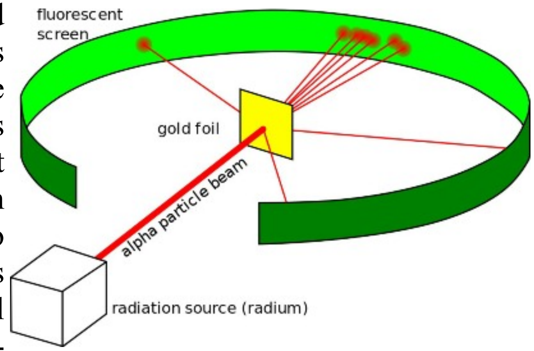
G. RUTHERFORD AND THE DISCOVERY OF THE NUCLEUS AND PROTON.

Dalton's Atomic Theory included the premise that atoms could not be broken down into smaller parts. Thomson's experiments falsified this premise by showing that the atom did indeed contain smaller parts.

Around the same time Thomson was doing his research, French physicist Henri Becquerel (1852-1908) and his colleagues Pierre and Marie Curie discovered radioactivity. They found that the elements they were working with not only emitted radiation but also turned into different elements with lower atomic masses.

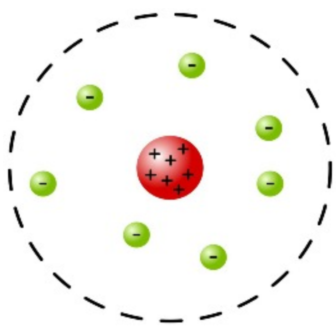
Visual #6-40

Thomson's student Ernest Rutherford (1871-1937) went beyond Becquerel's and the Curies' research into radioactivity. He identified and named two different types of radiation: (1) Alpha, which was later found by spectroscopic (color) analysis to be a helium nucleus consisting of two protons and two neutrons, and (2) Beta, which was later confirmed to be the same as the newly discovered electron.



Rutherford/Geiger/Marsden Gold Foil experiment
https://commons.wikimedia.org/wiki/File:Geiger-Marsden_experiment.svg
Attribution: Kurzon, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

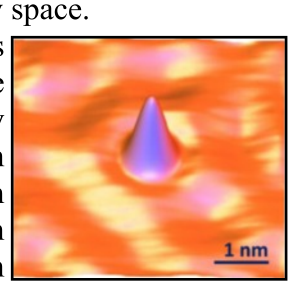
Between 1908 and 1913 Rutherford, Hans Geiger (for whom the Geiger counter is named), and Ernest Marsden performed an experiment designed to show that Thomson's Plum Pudding model was correct. Since radium was known to emit alpha particles, a sample was placed inside a lead box with a small opening that acted as a sort of gun barrel to direct the particles toward a thin gold foil. (Gold was selected because it is among the most malleable elements and can be beaten to only a few atoms thick.) Around the foil was a screen coated with material that produced a glow whenever it was struck by energetic particles. Since Rutherford accepted the Plum Pudding model, he expected that the alpha particles would go straight through. To his surprise, some were deflected at significant angles and others bounced almost straight back.



Rutherford's new model of the atom
https://commons.wikimedia.org/wiki/File:Rutherford_atomic_planetary_model.svg
Attribution: Bensteele1995, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

As a result of these experiments, Rutherford came up with a new model of the atom in which the positive charges were concentrated in a tiny nucleus and the electrons moved somewhere around it. (He did not know exactly where.) He later realized that there must be a particle responsible for positive charge, and that there must be different numbers of these particles in the nuclei of different elements. He was the first to call them protons.

Though Avogadro had estimated the size of atoms more than a century earlier, the experiments allowed scientists for the first time to indirectly measure their size as being on the order of 10^{-10} m, or 0.1 nm. The outer edge of the atom is defined by the electrons, but the nucleus is thousands of times smaller, around 10^{-15} m. A common comparison is that if the nucleus were enlarged to the size of a marble, the outer edge of the atom would be about a football field away. In between is empty space.



Scanning Tunneling Microscope image of a single Co atom
https://commons.wikimedia.org/wiki/File:STM_image_of_single_Co_atom.jpg
Attribution: NIST, Joseph Stroscio et. al., Public domain, via Wikimedia Commons

The miniscule size of atoms explains why they cannot be seen with even the most powerful optical microscopes. They are many hundreds of times smaller than the wavelength of visible light, which ranges from about 380 to 700 nm. Even with a Scanning Tunneling Electron Microscope (STEM), we can see a blur but cannot make out any of the details of the atom.

Rutherford received the Nobel Prize in Chemistry in 1908. In 1919 he succeeded

Thomson as director of the Cavendish Laboratory. Several of his students later received Nobel Prizes themselves. (Badash, 2022)

H. MOSELEY AND THE REARRANGEMENT OF THE PERIODIC TABLE.

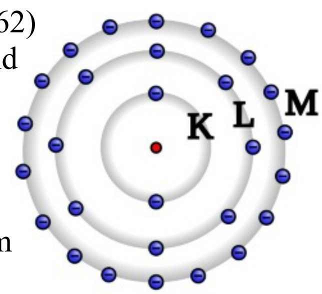
Rutherford's student Henry Moseley (1887-1915) solved a major problem with Mendeleev's periodic table. When it was arranged according to increasing atomic mass, some of of the elements did not have chemical properties similar to those immediately above or below them. While in his mid twenties, Moseley determined the number of positive charges in the nucleus (for which he coined the term *atomic number*) by analyzing the X-rays emitted under certain circumstances. He realized that rather than the atomic mass, the number of protons was responsible for chemical behavior. His 1913 rearrangement of the period table allowed him to correct the positions of several elements and successfully predict the existence of three new ones.

Unfortunately, Moseley's career was cut short when he was only 27 years old. He was killed at the Battle of Gallipoli in World War I. ("Henry Moseley," 2022.)

I. BOHR AND ELECTRON ENERGY LEVELS.

Visual #6-41

The Danish physicist Neils Bohr (1885-1962) studied under Thomson and Rutherford, and became a visiting faculty member at Rutherford's labs in 1914-1916 and later a permanent staff member. He was one of the first to blend Rutherford's atomic model with the newly developing field of quantum mechanics.



The Bohr atom with electrons orbiting in shells https://commons.wikimedia.org/wiki/File:Bohr-atom-shells-KLM.svg Attribution: Mike Run, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

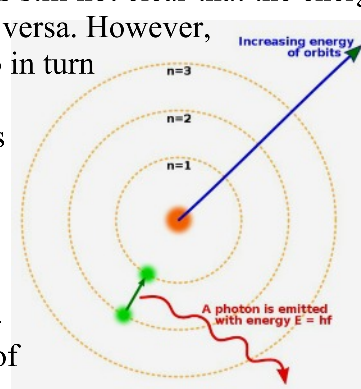
Rutherford had not proposed any specific locations for electrons in the atom. Bohr realized that since they had an opposite charge from the nucleus, they would have been pulled in unless they were in some sort of orbit. He proposed that they were in orbits with fixed energies, i.e., at fixed distances from the nucleus and that changes in orbits could not occur gradually, but only in sudden *quantum* jumps.

1. Emission and Absorption spectra

Electromagnetic radiation such as light can manifest itself as either a wave or a particle known as a photon. In 1900 the German physicist Max Planck (1858-1947) proposed that electromagnetic radiation could only occur in specific amounts or quanta, an idea for which he received the Nobel Prize in 1918. This became the starting point for quantum mechanics.

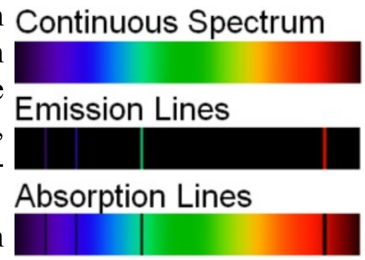
At the time of Bohr's work, it was still not clear that the energy of a photon could be transferred to an electron and vice versa. However, this was confirmed by Compton, who in turn won the Nobel Prize in 1927.

A photon has a dual nature. It acts as a particle in many circumstances but in others it acts as a wave whose energy level is determined by its wavelength. To calculate the energy levels of the simplest element, hydrogen, Bohr analyzed the wavelengths of light associated with it.



Bohr model - light emitted as electron drops from higher to lower energy. https://commons.wikimedia.org/wiki/File:Bohr_atom_model_English.svg Attribution: Brighter orange, CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>, via Wikimedia Commons

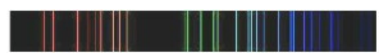
When a photon hits an atom, it may be absorbed or reflected. When absorbed, it increases the energy of one of the electrons orbiting the nucleus. The electron jumps to a higher level, then drops back to its original level in one or more steps. Bohr determined that for the single electron in hydrogen, there were multiple possible energy levels. (These correspond to the periods on the periodic table, each of which is defined by the highest principal energy level.) Each transition from lower to higher would absorb a specific amount of energy associated with a specific wavelength of electromagnetic radiation, and each transition from higher to lower would emit energy, often in wavelengths visible to humans as colors.



Hydrogen Spectrum
https://commons.wikimedia.org/wiki/File:Spectral_lines_en.PNG
Attribution:
User:Jhausauer, Public domain, via Wikimedia Commons

- If a large number of atoms receive energy in the form of electricity, X-rays, heat, and so on, they will then radiate the energy outward and may become a source of visible light. They produce an *emission* spectrum, which shows up on an instrument known as a spectroscope as bright lines against a dark background.
- When a large number of atoms are between an observer and an energy source such as white light, the atoms absorb specific colors. The result will be an *absorption* spectrum, which shows up as dark lines against a bright background.

Since each element has a unique number of electrons, each has its own unique emission and absorption spectrum. Scientists are able to analyze the spectra of objects to see what they are composed of, a process that is especially useful in forensics and analytical chemistry. Spectral analysis also enables us to determine the chemical composition of stars, no matter how far away.


Oxygen emission spectrum

2. **Energy sublevels.**

Visual #6-42

Bohr's analysis worked perfectly for atoms with only one electron, i.e., hydrogen and a helium ion that had lost one of its two electrons. However, other elements did not produce the clearly defined colors that Bohr's equations would have predicted. Nevertheless, Bohr's work, for which he received the Nobel Prize in 1922, is widely considered to have paved the way for later developments in quantum mechanics. The reason for the blurred lines was later explained by Schrödinger's wave equation, which allowed not just for eight principal energy levels but for sublevels close to the principal levels.

Throughout his life Bohr maintained close contact with other physicists. He had to hurriedly leave Denmark to avoid being arrested and forced to work for the Nazis during World War II. He eventually participated in the Manhattan Project that developed the first atomic bomb. (Aaserud, 2021.)

Bohr may not have intended to, but he answered the age-old question, *Why is the grass green?* It is because green is the only color that the grass does *not* use. It absorbs all the other colors and uses their energy but radiates the green back out.

J. FURTHER DEVELOPMENTS IN QUANTUM MECHANICS.

Many physicists struggled with why Bohr's idea of quantum jumps did not explain the colors emitted by elements other than hydrogen. A great many of them worked on the new field of quantum mechanics, but the following made some of the most significant contributions.

- Louis de Broglie (1892-1987) proposed that like electromagnetic radiation, electrons have a dual wave-particle nature. In fact, de Broglie's work showed that all matter, even planets and larger objects, had wave characteristics. He received the Nobel Prize in

1929 after the wave nature of electrons was confirmed by a stream of electrons being scattered and producing diffraction patterns.

- The Austrian physicist Erwin Schrödinger (1887-1961) used de Broglie's idea of "pilot waves," that when the electron was in place around the nucleus it was actually a wave whose wavelength determined its position.

> We now use the term "orbital" rather than "orbit" to describe an electron's position in the atom. An orbital is not an observable thing but is a mathematical description of where electrons are likely to be 90% of the time.

The accomplishment for which Schrödinger is best known is his mathematical development of the wave equation $\hat{H}\Psi = E\Psi$. The derivation of the equation is extremely complicated and involves highly advanced math, but it allows scientists to predict a wave's position. In order to do so, the wave equation requires the use of imaginary numbers to describe the behavior of real phenomena. No one has yet found a better way to describe real phenomena with real numbers.

Schrödinger received the Nobel Prize in 1933, the same year he left Germany due to his opposition to Nazi politics. He later had to leave Austria when it was also taken over by the Nazis.

- The German physicist Werner Heisenberg (1901-1976) wrote hundreds of papers and was one of the most influential figures in the development of quantum mechanics. He is best known to non-physicists for his Uncertainty Principle: the more precisely we know a subatomic object's position, the less precisely we know its velocity, i.e., where it's going. He showed that this was not just due to uncertainty in measurement but to the dual wave-particle nature of matter. (He won the Nobel Prize in 1932.)

> One of the implications of quantum mechanics is that matter, which can be seen, is ultimately composed of waves, which cannot be seen. The Bible predicted this almost 2,000 years ago: "Through faith we understand that the worlds were framed by the word of God, so that things which are seen were not made of things which do appear." Heb. 11:3

When an electron is not attached to an atom, it usually acts like a particle (except that a stream of electrons can be diffracted. However, when it is inside an atom, the present model shows it as something like a throbbing wave rather than a particle.

Historical note: Heisenberg was a Nobel-Prize winning German scientist. He had no choice but to be drafted into the ranks of Hitler's scientists, where he was assigned to work on the development of nuclear energy. After the war, it was revealed that Heisenberg was aware of all the details of how to build an atomic bomb, but deliberately misguided the project so that Hitler would not acquire such a weapon. (Charles, 1992)

K. CHADWICK AND THE NEUTRON.

Visual #6-43

Quantum mechanics does not have much to do with practical everyday chemistry. The classical concept of particles is much more relevant to the way atoms combine into compounds or compounds separate into atoms.

James Chadwick (1891-1974), another of Rutherford's students, completed the model of the particulate atom composed of protons, neutrons, and electrons. In 1920 Rutherford had proposed that since the masses of atoms could not be accounted for by protons alone, there must also be a neutral particle. In 1923 Chadwick, now the assistant director of the Cavendish Laboratory under Rutherford, performed a series of experiments to try to detect this particle. Following the ideas of Frédéric and Irène Joliot-Curie, he bombarded samples of light elements with alpha particles emitted by the radioactive element Polonium and observed the effects on a detector made of a very low-tech material, paraffin wax. Whatever particles were coming out of the beryllium were knocking hydrogen nuclei out of the wax. Since he did not think charged particles could have penetrated deeply into it, Chadwick proposed that the particles must have had no charge. He named them neutrons. (This Month in Physics History, 2007.) In 1935 he received the Nobel Prize for his discovery.

> The discovery of the neutron falsified the part of Dalton's Atomic theory that said all atoms of the same element were identical. It turned out that though the number of protons (the Atomic Number) in all atoms of a particular element are the same, the number of neutrons in the nucleus may vary. Different forms of the same element that have different numbers of neutrons are called isotopes.
>
> The number of neutrons affects the stability of the atom in some way we do not yet understand. For instance, Uranium-235 is fairly stable, but if a single neutron is added it turns into U-236, which can produce a chain reaction resulting in a nuclear explosion.

Chadwick was keenly aware of the potential impact of his discovery. For the first time, scientists and the government officials they worked for would be able to deliberately split heavier atoms and release enormous amounts of energy. Chadwick realized that nuclear bombs were now not only possible but inevitable. He felt that he had unlocked the door, and said that for the rest of his life he had to take sleeping pills every night. (Weiner, 2022)

L. NUCLEAR ENERGY AND ITS RAMIFICATIONS.

Einstein's famous equation $e = m\,c^2$ shows that if even a small amount of matter can be converted into energy, the output will be far beyond anything previously known. After Chadwick's discovery of the neutron, other scientists learned how to manipulate it to cause atoms to split in a reaction called *fission*.

> Memory aid: fiSSion has two of the letter S together, a convenient place to SPLIT. FUsion has a "U," because it UNITES two atoms.

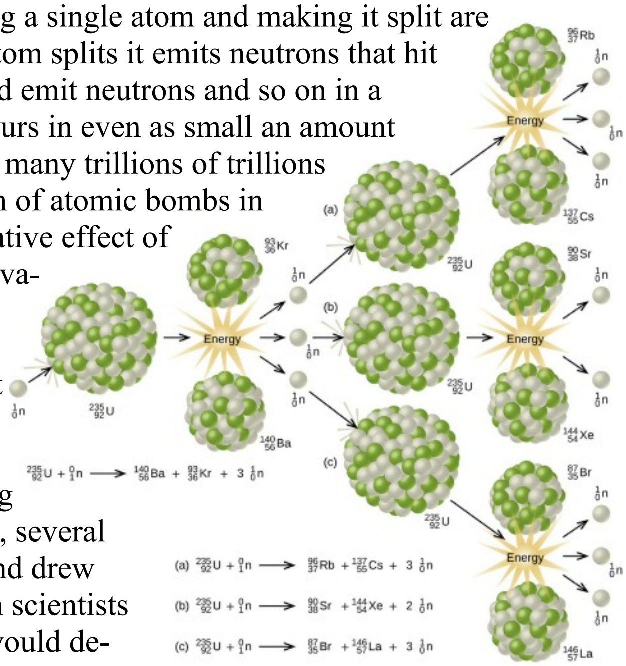
When a Uranium atom splits into two roughly equal parts, there is a tiny "mass defect." The missing mass is converted into energy in accord with $e = mc^2$.

1. The Manhattan Project. ("Manhattan Project," 2022)

Visual #6-44

The effects of a single neutron striking a single atom and making it split are very small. However, once the first atom splits it emits neutrons that hit nearby atoms and make them split and emit neutrons and so on in a chain reaction. If a chain reaction occurs in even as small an amount of uranium as one kilogram (2.2 lbs), many trillions of trillions of atoms are involved. The detonation of atomic bombs in World War II showed that the cumulative effect of all the atoms splitting is enough to devastate a city.

Chadwick's work showed scientists around the world the way to split atoms. Though atomic bombs might have been developed eventually, World War II was the catalyst to bring them into existence. As early as 1939, several years before Japan attacked the US and drew it into the war, a number of American scientists were concerned that Nazi Germany would develop a nuclear bomb. They petitioned President Roosevelt to establish a project to develop the bomb first. Even Albert Einstein (who had no direct involvement in the project) wrote a letter to the President encouraging him to do so.



Fission chain reaction. https:// commons. wikimedia.org/wiki/File:CNX_Chem_21_04_ChnReact1.png
Atribution: OpenStax, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons

The project to develop nuclear fission for military use began unofficially in 1940, before the US entered the war, in collaboration with scientists from Great Britain and Canada. Shortly after the US declared war in Dec. 1941, the project was designated the Manhattan Project because it began under the auspices of the Manhattan District of the US Army Corps of Engineers. (Research and development was done in this country because the US was considered to be less susceptible to German attack.)

The project eventually included multiple locations across the country, including several new top secret cities that sprang up almost overnight. Only the top officials knew what they were working on. Gen. Leslie Groves was in charge of military operations, while the scientific aspects were under the authority of physicist J. Robert Oppenheimer. Other scientists involved included Hans Bethe, Felix Bloch, Niels Bohr, Klaus Fuchs, James Chadwick, Enrico Fermi, James Franck, Otto Frisch, Ernest Lawrence, Glenn Seaborg, Emilio Segrè, Leo Szilard, Edward Teller, and John von Neumann to name just a few. Several had new elements on the periodic table named after them.

The project produced three bombs, dubbed Trinity, Fat Man, and Little Boy. In order to be sure the bombs would work, Trinity was detonated in the New Mexico desert on July 16, 1945 while military and scientific personnel watched from bunkers about six miles away. Oppenheimer, fully aware of his personal responsibility in developing the bomb, quoted one of the Hindu scriptures as he watched:

> "Now I am become death, the destroyer of worlds."

Shortly afterward, the other two bombs were dropped on Hiroshima and Nagasaki, ending the war.

The bombs available now are far more powerful than the earliest ones. Instead of depending on nuclear fission, in which the atom is split and only a tiny portion of its mass is converted into energy, they now use nuclear fusion in which two atoms are united into one and a much higher percentage of the mass is converted into energy.

2. **Peaceful uses of nuclear energy.**

Scientists and engineers have learned how to control nuclear fission (NOT fusion, which requires temperatures of millions of degrees).

Visual #6-45

- It is used as a heat source in nuclear power plants. Instead of burning coal or oil, a nuclear reaction produces the heat used to boil water, thereby producing steam to spin turbines and produce electricity.

  Except in case of accidents like those at Chernobyl, they do not release radiation into the environment and are the cleanest powered source available. One of the biggest problems is what to do with the partially guised up fuel rods. Everybody wants cheap electricity, but nobody wants radioactive waste where they live. (Perhaps you have heard of the acronym NIMBY, short for "Not In My Back Yard.")
- Small scale nuclear power plants are used to power some space probes. They use a Stirling heat engine expected to run for thousands of years on a small amount of fuel.
- Radioactivity is used in medicine for obtaining diagnostic images.
- It is used to bombard and kill cancer tumors.
- It is used in large scale food preservation. It kills all the bacteria, insects, and so on that hide in food. (You still eat them, but now they're dead.)
- Whether or not you consider this a peaceful use, nuclear reactors produce electricity to run the engines on many military vessels.

So far, all the non-military uses of nuclear energy have used fission rather than fusion, which we do not yet know how to control.

CHAPTER 6 REVIEW QUESTIONS

1. What did the ancient Greeks think everything on earth was made of? ____________________
____
2. Suppose you see a bag of bread at the grocery that says "Contains no chemicals." Why shouldn't you trust the label? ____
3. What does the Second Law of Thermodynamics have to do with how the sun's energy first came together? ____
____
4. How can chemists tell something is an element? ______________________________________
____
5. How can chemists tell something is a compound? _____________________________________
____
6. How can chemists tell something is a mixture? _______________________________________
____
7. What is the difference between an atom and most types of molecules? ___________________
____
8. How do chemists find out the chemical properties of a material? _______________________
____
9. What does a chemical change automatically cause? ____________________________________
____
10. What is the most common state of matter in the universe? ___________________________
11. Most elements on the periodic table are ______________________________________.
12. How does the tendency of elements on the left side of the periodic table to attract electrons compare to the elements on the right side? ___________________________________
13. What does the Bible hint at about the Strong Nuclear Force? _________________________
____
____
14. Which shell of electrons in an atom is most important in chemical reactions? ____________
____
15. Give two examples of common types of chemical reactions. __________________________
____

16. What often causes molecules to have a three-dimensional shape rather than being flat? ______

____

17. Who was the first reported person to propose the idea of atoms? ________________________

18. Why was the idea of atoms discarded for about 2000 years? ____________________________

____

19. Who first proposed the modern theory of the atom? ____________________________________

20. Who is given credit for developing the Periodic Table? _______________________________

21. What observation led Thomson to conclude that there must be particles smaller than an atom?

____

22. What model did Thomson propose for where the electrons were when not flowing? ________

____

23. What material did Rutherford and his colleagues use in their experiment to discover that the atom had a nucleus? ____

____

24. What is there about the size of the atom and the wavelength of visible light that does not allow us to see atoms even with the most powerful optical microscopes? ______________________

____

25. How did Bohr explain the colors of light emitted by Hydrogen? ________________________

____

26. How can scientists determine what elements are present in stars without ever going to them?

____

____

27. How does the work of Schrödinger fit with Hebrews 11:3? _____________________________

____

28. How did Chadwick's discovery of the neutron affect him personally?

____

____

29. What are some non-military uses of nuclear energy? ___________________________________

____

CHAPTER 6 REFERENCES

Melhado, Evan M. "Jöns Jacob Berzelius." *Encyclopedia Britannica*, Jul 20, 1998, updated August 16, 2022. https://www.britannica.com/biography/Jons-Jacob-Berzelius.

"Jacob Berzelius." Famous Scientists. famousscientists.org, January 25, 2017. Accessed August 23, 2022. https://www.famousscientists.org/jacob-berzelius/.

"J. J. Thomson Autobiography." Department of Physics. Univ. of Cambridge Cavendish Laboratory, August 13, 2013. Last modified August 13, 2013. Accessed August 23, 2022. https://www.phy.cam.ac.uk/history/electron/autobiography.

Badash, L. "Ernest Rutherford." *Encyclopedia Britannica*, May 2, 2022. https://www.britannica.com/biography/Ernest-Rutherford."Henry Moseley." *Encyclopedia Britannica*, August 6, 2022. https://www.britannica.com/biography/Henry-Moseley.

Aaserud, F.. "Niels Bohr." *Encyclopedia Britannica*, November 14, 2021. https://www.britannica.com/biography/Niels-Bohr.

This Month in Physics History. American Physical Society, May 2007. Last modified May 2007. Accessed August 25, 2022. https://www.aps.org/publications/apsnews/200705/physicshistory.cfm.

Weiner, Charles. "James Chadwick - Session IV." Oral History Interviews | James Chadwick - Session IV | American Institute of Physics. American Institute of Physics, April 26, 2022. Last modified April 26, 2022. Accessed August 25, 2022. https://www.aip.org/history-programs/niels-bohr-library/oral-histories/3974-4.

Charles, Dan. "Heisenberg's Principles Kept Bomb from Nazis." *New Scientist.* New Scientist, September 4, 1992. Last modified September 4, 1992. Accessed August 23, 2022. https://www.newscientist.com/article/mg13518370-300-heisenbergs-principles-kept-bomb-from-nazis/.

Editors of Encyclopaedia Britannica. "Manhattan Project." *Encyclopedia Britannica*, March 30, 2022. https://www.britannica.com/event/Manhattan-Project.

This page intentionally left blank