

# PHYSICS & CHEMISTRY Study Guide

A knowledge of the principles of physics makes all sciences, especially chemistry, easier to understand, so we will begin with a survey of physics. As with any other subject, physics can be simple, but much of it is complex. The key to understanding the more difficult concepts of physics depends on your mastery of the simpler ones. The concepts covered in this text are presented in an order which will help students review their knowledge efficiently – beginning with the simple and going from there. For this reason, first-time students should follow this document in order; experienced students should feel free to browse at random.

## I. PHYSICS

### 1. Fundamental quantities

One aspect of physics that becomes obvious to all physics students can be phrased in at least two ways: “Mathematics is the language of physics” and “Mother Nature is quantitative.” What this should mean to you is simply this: *The rules of physics (or “laws” as they are often called) frequently involve formulas or equations that connect **quantities**.*

The **quality** of something is a ranking - somewhat vague - that could be illustrated as follows: “Dion is a much better runner than I am.” The **quantity** of something is also a ranking, but involves making numerical measurements and then comparing them. “Dion runs a 11.5 second 100 meter dash. I’ve never broken 12.9.”

You need to become familiar with quantities measured in physics (you already know some of them!) so here are a few of them. We’ll divide them into two categories: **fundamental quantities** and **derived quantities**. Believe it or not, physicists can quantify (that is, put numbers on every quantity in the universe) using only *seven* fundamental quantities. Everything else can be derived from those seven! Here are the fundamental seven:

Quantity	Name	Abbrev.	
length	meter	m	
mass	kilogram	kg	
time	second	s	
charge	coulomb	C	
luminosity	candela	Cd	
matter	mole	mol	
temperature	kelvin	K	

By “derived” units we mean any *combination* of the seven fundamental units. A common example would be speed (or velocity) which is the ratio of length to time. A physicist would prefer to use units of meters per second. Most of us prefer to use miles per hour!

## 2. Scientific Notation

Quantities measured by scientists (especially physicists and chemists) range from incredibly small to unimaginably large. Writing those numbers becomes cumbersome, so the system of **scientific notation** is frequently used. In this system we use powers of ten to simplify the writing. For example, you can now find personal computers for sale that have processor speeds of one billion calculations per second. Numerically, one billion is 1,000,000,000. But we can also understand one billion as ten multiplied by itself nine times, so we can represent one billion as  $1 \times 10^9$ . To make it even easier, there are names assigned to the various powers of ten (see table below). In addition, when naming something that happens repeatedly (or *periodically*) we can use a derived metric unit. In the case of the computer, we can use the **hertz**, which stands for “per second.” For example, if a computer has a processor speed of one gigahertz, using abbreviations we can make it even simpler: 1 GHz. Though it seems like a lot of work, in the end it makes expressing quantities much simpler.

We’ll add more derived metric units as we progress, but here is a list of some of the powers of ten prefixes that you should know:

Number	Sci. Not.	Prefix Name	Abbreviation
1,000,000,000,000	$10^{12}$	tera	T
1,000,000,000	$10^9$	giga	G
1,000,000	$10^6$	mega	M
1,000	$10^3$	kilo	k
0.01	$10^{-2}$	centi	c
0.001	$10^{-3}$	milli	m
0.000,001	$10^{-6}$	micro	$\mu$
0.000,000,001	$10^{-9}$	nano	n
0.000,000,000,001	$10^{-12}$	pico	p

Note: that symbol for micro is a lower case Greek “mu”. It looks like a “u”, but add a long introductory tail to it when you write it. To find it on a computer, locate the font named *Symbol* and type the letter *m*. Memorizing the above table would be a good thing to do - it’s like learning new words in a language class.

### 3. Kinematics - the study of motion

One of the more basic topics in physics is motion. Motion is nothing more than an object changing its location, but it isn’t always as simple as it looks.

When something changes location, we can quantify that change in a variety of ways. You might run so many meters in a race or ride so many miles on a trip. But something else that must change when motion occurs is **time**. Time is one of the hardest quantities to define. In fact, lean back in your seat right now and try to do it. Ask a friend to do it. Here is a way to get started: try to imagine a world where nothing is allowed to move. Nothing. Your eyes can’t blink, your heart doesn’t beat. Every atom and molecules stays put. Now you have the one scenario where you *don’t need time* because you don’t need motion! So time is somehow related to things changing location. It is sort of a separation of events.

When something moves we can put a number on how far it moved and how long it took to move. But we can quantify much more. If you divide the distance you moved by the time you took we get a new quantity: **speed**. We define **average speed** as the total distance moved divided by the total time taken. (Watch a car race on TV – they make a big deal of it!) We need to add another quantity here - **velocity**. Velocity is not just a fancy synonym for speed. We define **velocity** as the **displacement** during motion divided by the time taken. **Displacement** is defined as the final location of an object compared to its original location. Distance and displacement are the same if no direction change occurs. If you run a lap around a 100 meter track your distance

traveled will be 100 meters, but your displacement will be zero! More on this later.

We know that race cars don't drive at the same speed all the time. They speed up or slow down. When they do this, we say they have **accelerated**. **Acceleration** is defined as the change in velocity of an object divided by its change in time. Acceleration is positive if you speed up and negative if you slow down. If a certain sports car can accelerate from zero to 60 miles per hour in 4 seconds, we could say its acceleration is 60 divided by 4 or 15 miles per hour per second. That means each second it accelerates it gains 15 miles per hour. After one second: 15 mph; two seconds: 30 mph; three seconds: 45 mph; four seconds: 60 mph!

An object that is *not* accelerating is said to be in **uniform motion**.

#### 4. Vectors and Nonlinear Motion

We need to learn some special mathematics here to proceed with our physics. The types of measurements that physicists make fall into two main categories: quantities that can be reported with simply a number and a unit (**scalars**) and quantities that need a direction in addition to the number and unit (**vectors**).

We can use the quantities **distance** and **displacement** here as an example. If I told you that there was a \$10 bill hidden in the room you are in right now and that it was exactly 10 feet from where you are sitting, that "10 feet" would be called a **scalar**. Look around - there are a lot of places 10 feet from where you are sitting. However, if I added direction to the distance, that quantity would become a **vector**. Let's say the \$10 is 10 feet away "due east". Now there is just one place to look for the \$10. (There are other systems for indicating direction such as **polar coordinates** and **unit vector notation** but we don't need them just yet).

Imagine taking a walk in two parts: you walk three blocks and stop to meet a friend. Then you and your friend walk an additional four blocks. How far have you walked? If I asked you for the *distance* you walked, your answer of "seven blocks" is correct. But, if I wanted to know your *displacement* you would need more information. It turns out your displacement could be anywhere between seven blocks and one block. If you first had walked three blocks north and then four blocks south, you would be one block south of where you started. Your displacement would be *one block south*. But if you had first walked three blocks north and then an additional four blocks north, you'd be seven blocks north. *Seven blocks north* would be your displacement. But what if you walked three blocks north and then four blocks east? If you sketch this out on a map you'd find that you are actually five blocks from where you started. You could walk back to where you started (assuming there were no buildings in the way) with a walk of only five blocks. We could have stated your displacement in this case as "five blocks northeast". Our point here is that there is more to motion than direction.

There are three types of motion we'll look at that involve a change in direction. These are: circular motion, trajectories and relative motion.

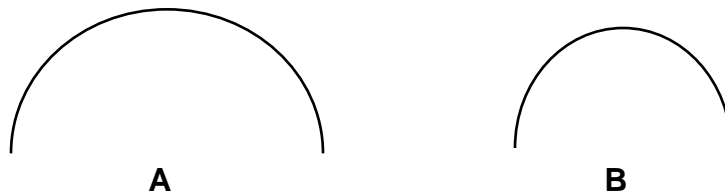
## 5.1 Circular Motion

When something moves in a circle, even if it isn't changing speed, it is accelerating. The **velocity** of an object is its speed plus its direction. Velocity is a **vector**. Since something moving in a circle is changing direction, its velocity is changing. If something has its velocity changing, it is accelerating! Sir Isaac Newton (while on an extended vacation from college) was able to quantify this acceleration and show that the direction of the acceleration was towards the **center** of the circular path. Because of the *direction* of the acceleration, it is called **centripetal acceleration**. "Centripetal" means "center seeking." Newton also found that the size of the acceleration could be gotten by squaring the speed of the moving object and dividing by the radius of the circular path. So, if you are turning a corner in a car and it is a "tight" turn (small radius), you may have a large acceleration. Likewise, if you increase the speed of a turn - say, *double* the speed - the acceleration will increase - *four* times (two squared) in this case.

## 5.2 Trajectories

A **trajectory** is the path of a **projectile**. A projectile is anything that is thrown, kicked, hit, tossed, etc. The path the projectile takes is called its "trajectory." Since a ball flying through the air is changing both its position and velocity, we can use vectors to break the motion into two parts: first, the horizontal motion which (ignoring air resistance) is uniform motion. Second, the vertical motion is uniform accelerated motion. If you put these together, it turns out the path of a baseball (or pencil) is a parabola.

If the Cubs are at bat, if there is any air resistance (and there usually is, for example: wind blowing IN at Wrigley Field) the trajectory of Moises Alou's hit is affected. In this case, the wind is trying to keep the ball in the park. Let's call the parabola representing this trajectory parabola *IN*. When the wind is blowing OUT at Wrigley Field, the trajectory of Moises' hit will also be affected, but in a different way than before. Let's call the parabola representing this trajectory parabola *OUT*. Which one of the below do you think is which?



As you might imagine, picture A is the trajectory of a solid hit when the wind's blowing out.

Picture B is the unlucky situation when the wind is blowing straight off the lake and over Wrigley's left field.

We'll skip all the math here, but please note a couple of results of what we've reviewed. First, how high and how far a projectile will go depends on the *square* of the speed. So, if you start getting stronger and can throw a baseball with *twice* the speed you could before, it won't go twice as far - it will go four (two squared) times farther! Secondly, the angle at which you throw something affects how far it will go. It turns out that throwing most objects at  $45^\circ$  above the horizontal ( can you guess why we say "above the horizontal"?) will get maximum horizontal range. So, if you field a ball in deep center field and need to throw the ball as far as possible, do the following: try to get a good  $45^\circ$  angle on that ball and put your back in it.

### 5.3 Relative Motion

"Relative motion" is a term used to describe a situation where something is moving in something that is moving. Reread that sentence! It's not double-talk, but it *is* something that takes some careful thinking to be comfortable with. What we are adding here are velocity vectors.

We have previously noted that when the wind is "out" at Wrigley Field, fly balls carry farther. We all know that walking up an UP escalator gets us to the next level faster. Walking down an UP escalator, on the other hand (aside from being dangerous), wouldn't make for much progress, or perhaps non at all! Or you might end up going up while you're walking down!

This is interesting to think about. If Mr. B decides to walk down an UP escalator, he may believe for a few seconds that he really is *moving down*. But Ms. A, who's waiting for him at the bottom, sees Mr. B walking in place and not *moving anywhere*. We're in the realm of vectors again and the result is simple. A motion that is observed by someone who is not moving ("fixed") is the **vector sum** of the motions involved.

An example: let's imagine there is a small stream or river flowing by us at 3 mph. Let's pretend we're in a canoe and we can paddle at 4 mph in still water. If we paddle *downstream*, someone on the shore ("fixed") would watch us go by at 7 mph ( $3 + 4 = 7$ ). If we then decide to paddle upstream, our fixed observer would see us moving at  $4 + (-3) = 1$  mph relative to the "fixed" shoreline.

But, what if we decide to paddle *across* the stream? If you assume the stream is moving from your left to your right and we paddle straight across in front of us, we'll end up "across and to the right". If you go back to the vector part of this packet you'll see that "3 up" plus "4 over" equals "5 at an angle." Vectors again.

## DYNAMICS - GRAVITATION - MOMENTUM

### 6. Dynamics

All the physics we have looked at up to this point was well understood 400 years ago.

By about 1600, Galileo had worked out many of the details about how things moved. The question that hadn't been answered, though, what *why* do they move like they do. Sir Isaac Newton answered the question of *why* when he developed the field of **dynamics**. Dynamics is the part of physics that explains *why* we see baseballs follow parabolic trajectories and why some things accelerate and some things do not. The study of dynamics adds two new concepts to explain motion: **force** and **mass**.

**Mass** is often defined as the “quantity of matter” of an object. In physics, though, we add two more important definitions. The word **inertia** is used to describe an object's tendency to want to keep doing what it is doing in terms of motion. Mass can be defined as the measure of an object's inertia. So, a very massive object has a lot of inertia and resists changing its motion. A lineman in football tends to be massive and have a lot of inertia. As a result, if he isn't moving you'll find it is hard to get him out of the way. If he *is* moving, you'll find it hard to change the path of his motion.

A second way of defining this effect is to say the “Mass is the resistance to acceleration.” The more mass something has, the harder it will be to accelerate it. A softball and a shot-put are about the same size, but the mass of a shot-put is very much greater. You can't accelerate a shot-put like a softball. The shot-put won't go as far.

You can define a **force** as simply a push or a pull — and that is accurate enough. More complicated is the idea of a **net force**. When a net force exists, you will see a *change* in the motion of an object. For example, if you look closely at a box of cereal, you will see “net weight” listed somewhere on the package. The net weight is how much *cereal* is in the box. If you weigh a box of cereal on a scale, the scale won't read how much cereal is there; it will include the box, the bag, the glue, the ink - everything. What is important (when you're hungry) is the net weight of the cereal.

The same is true with forces. The net force indicates what motion an object has. Imagine two kids tugging on a toy. If each pulls with the same size force and they pull in opposite directions, the toy won't go anywhere. According to physics, the net force on the toy is zero (remember: we're adding vectors here!  $2 + 2 \text{ can} = 0$  if the vectors are in opposite directions.)

## 6.2 Newton's First Law of Motion

In his **First Law of Motion**, Isaac Newton said that if the net force on something is zero, then it's acceleration will be zero.

There are two scenarios here:

- 1) If an object is not moving and the net force on the object is zero, then the object is not going to start moving on its own.
- 2) If an object is *already* moving and the net force on it is zero, then it will continue to move at the *same speed* in a *straight line* (in other words, *not accelerate*.) This part of the First Law is harder to understand. That's because we are used to

seeing ordinary objects that are moving (for example: a ground ball hit into the outfield) slowing down and stopping all by itself. Why did it stop? Why did it negatively accelerate? According to Newton, there must have been a net force acting on the ball. One force we often ignore (because we don't easily see it) is due to air resistance and is called **friction**. Friction is a force that occurs when two things rub against each other. There are four main types of friction:

1) **Static** - when the two objects *don't* move relative to each other. An example would be between the sole of your shoe and a basketball court when you *don't* slip.

2) **Kinetic** - when the two objects *do* move relative to each other. An example would be when a car skids to a stop and you see tire marks on the pavement.

3) **Rolling** - when a round object rolls on a surface. An example would be a bicycle tire rolling on a sidewalk.

4) **Fluid** - when an object moves through a fluid. A fluid is a gas or a liquid. An example is the air resistance you feel when you run fast. World-class athletes often wear high-tech uniforms in events like sprinting and speed skating to reduce the fluid friction.

### 6.3 Newton's Second and Third Laws of Motion

In Newton's **Second Law of Motion** he combines the ideas of mass, force, and acceleration. There are two parts to his second law:

1) The acceleration of an object is directly proportional to the net force on it. The harder you push or pull on something, the faster it will accelerate. If you double the net force on something, its acceleration will double.

2) The acceleration of an object is **inversely proportional** to its mass. The more massive an object is, the harder it is to accelerate. If you try to toss two rocks and one of them is twice as massive as the other, it will only accelerate at *half* the acceleration of the other. In addition, the acceleration of the object will be in the same direction as the net force. Force and acceleration are both vectors. In a formula: Net force = mass X acceleration.

In his **Third Law of Motion**, Newton makes the discovery that in our universe, forces always come in pairs that are equal and opposite. Basically it means that an object doesn't *create* a force; forces are interactions between two things. If you hit a volleyball with your hand, the volleyball hits your hand with the same size force. Think about running. If you want to run forward, your feet have to push backward. If you want to turn and start running to the right, your feet have to push to the left. A classic summertime example of this law is all of the broken bats in Major League Baseball. The bat hits the ball; the ball hits the bat.

This Third Law is often stated as: "For every action there is an equal and opposite reaction."

## 7. Types of Forces

Although there are countless specific forces in the universe, physicists have been able



to file them all into a mere four categories:

1) **Gravitational force**. This is a force that exists between any two masses. It is a very weak force, so at least one of the two masses has to be huge in order to feel the force. For example: at this moment you do not feel the force of gravity between you and the person sitting near you. The force is there! It's size is negligible. But, planet Earth is very massive and you *do* feel the force between you and it. By the way, if the earth pulls on you with a force of 150 pounds, you pull on the earth with that same 150 pounds. Because of its huge mass, you don't affect the motion of the earth. But, the earth certainly affects your motion!

2) **Electromagnetic force**. This force exists between objects that are "charged." The common charged particles in our universe are the electron and proton found in atoms. This is a very strong force. In fact, it is holding you together at this very moment. In addition, most common forces we experience in our lives (except for gravity) have the electromagnetic force as their real origin. Hitting a volleyball involves the charged particles in your hand interacting with the charges in the volleyball.

3) **Strong nuclear force**. This is the force responsible for holding atomic nuclei together. It is incredibly strong (hence the name!), but it only acts over very small distances. As a result, it is only important for interactions inside the atomic nucleus. However, the extraordinary energy from atomic bombs and nuclear power plants comes from this force.

4) **Weak nuclear force**. This is another force whose importance is restricted to tiny distances. It is exotic enough that we'll say no more!

An aside:

A primary responsibility for physicists is to take our complex universe and explain it in simpler and simpler terms. They've obviously done that with forces. Narrowed it down to four (and only two are really important for you and me). However, they've made a connection between the electromagnetic and weak nuclear forces. It is possible to write the list with only *three* forces, one of them being the **electroweak force**. It's not often done, but do realize it is a lofty goal (a "Holy Grail") for physicists to find a single force to explain everything. Physicists call it the **Grand Unified Theory** (GUT, for short) and many physicists around the world have taken on the challenge of finding it. That assumes, of course, that it even exists!

## 8. Momentum

Another concept and quantity that comes directly from Newton's Second Law is the idea of **momentum**. Momentum is the product of an object's mass and its velocity, and is often called "inertia in motion." To have momentum you must have both mass and motion. The larger each is, the larger the momentum. Another quantity that comes from Newton's Second Law and momentum is **impulse**. Impulse is simply the product of the net force exerted on an object and the time over which that force is exerted.

This is important because the change in momentum of an object exactly equals the impulse exerted on it. If you want to change the momentum of an object (say a baseball coming toward home plate), the more force you exert and the longer you exert that force, the more that object's momentum will change. In many sports, coaches often emphasize "follow through" in players' swings for this very reason — exerting control over the ball or equipment for the longest possible time.

Momentum is a quantity that is **conserved**, that is, the total amount of it stays the same. It doesn't go away, it just transfers from one object to another. If one object loses momentum, the other picks it up. In addition, as we have already seen, the force on each object in a collision must be the same (Newton's Third Law). Why is it, then, in a collision between a large truck and a small car that the car usually "loses"? The answer is in the mass of each. Since each vehicle experiences the same force and the same change in momentum, the one with less mass experiences a greater acceleration. And, acceleration is what hurts it.

## 9. Work and Energy

The word **work** has been around for a long time. We can define it in many ways. In physics, as you may expect, we handle work a little differently — we *quantify* it. You can quantify your work in a class by saying, "I studied one hour a night for that course." In the workplace your work might be quantified by how many much you are paid per hour. Automobile repair shops might say, "That will be a two and a half hour job."

Physicists have quantified work in a very simple way. Work is the product of an applied force times how far the object being worked on moves in the direction of that force. If you lift a book, you did work. If you stand still holding a book, you're not doing any work. If you throw a baseball you do *positive* work. When you catch a baseball you do *negative* work (the force was in the opposite direction of the movement). If you measure the applied force in newtons and the distance moved in meters, the resulting work unit is called the **joule** (rhymes with "school"). If you lift a regular hamburger three feet high, you've done about one joule of work. A joule is not a very large amount of work. If you walk up one flight of stairs, you will do several thousand joules of work.

If you recall, when an impulse is done on an object, the result is a change in momentum for that object. In a similar way, when work is done on an object, the result is a change in energy for that object. **Energy** is defined as the ability to do work. But when you do work, energy changes! This seems like some sort of double-talk, but it isn't. It takes energy to do work. When work is done, energy changes form or moves from object to object. What is very important here is that the total amount of energy in the universe appears to be conserved. You'll recall that this means the total amount doesn't change - it just keeps moving around.

### 9.1 Kinetic and Potential Energies

Here are some different kinds of energy. They fall into a few simple categories.

1) **Kinetic energy** is the energy something has when it is moving. Does something moving have energy just because it is moving? Try standing in the way of a speedy running back on a football field and you'll quickly find that he *can* exert a force on you over a distance! Kinetic energy is quantified in the following way:

$$KE = 1/2 \times \text{mass} \times \text{speed squared.}$$

2) **Potential energy** is a form of energy that is stored and can be used at a later time. A good example is when you lift something. You have to do work to lift something, but when you are done, where's the energy? We say it is stored in a form called **gravitational potential energy**. At any time in the future (now, tomorrow, or ten years from now) you can let go of this object you just lifted and it will fall. As it falls, it can do work on something if it strikes it (i.e. exerting a force over a distance).

Some other forms of potential energy are:

- **elastic potential energy** (when you stretch something "springy" that will return to its original shape or position. Example: when a bowstring is stretched in a bow and arrow.

- **chemical potential energy** (when positions of atoms in molecules are rearranged). Example: gasoline that you put into a car.

- **nuclear potential energy** (when protons and neutrons are rearranged in atomic nuclei). Example: nuclear power generation in submarines and electric power plants.

Just like momentum, energy is something that physicists are convinced is conserved. That means if you have 5 joules of energy to begin with, then after work is done there will still be 5 joules of energy around. It may be in some other form, or some other object might possess it, but there will still be 5 joules of energy. For example, if you hold a basketball above your head and let it fall onto a hard surface, it will rebound up into the air again.

Some energy conversions are:

- your body's food (chemical) energy to gravitational potential energy
- gravitational potential energy into kinetic energy
- kinetic energy into elastic potential energy (deformed basketball)
- elastic potential energy into kinetic energy
- kinetic energy into gravitational energy

Problem: the ball will not bounce back up as high as the point where you released it. We're missing some energy here! Yes and no. As far as mechanical energy is concerned, something is missing. (**Mechanical energy** is defined as the sum of the kinetic and potential energies.) As far as total energy is concerned, we're not missing any energy. **Total energy** includes an energy form called **heat energy** which is the internal, random kinetic energy of the atoms and molecules. This is still a form of energy, but it isn't a very useful form in most situations. For the most part it is considered a wasted form of energy, but if you happen to need heat energy that wouldn't be so.

We'll look at heat energy again when we investigate energy in the chemistry sections that follow, but here are a few ideas that you should know.

1) The **temperature** of an object is a measure of the **average kinetic energy** of its atoms and molecules.

2) Since you can't have a *negative* kinetic energy, if you could get an object to lose all of its kinetic energy, it would have no temperature. We call this temperature **absolute zero**.

3) There are three common temperature scales in use today.

Scale Name	Unit Abbreviation	Temperature of	Temperature of	Temperature of Boiling
<b>Celsius</b> (formerly "centigrade")	°C	-273.15	0	100
<b>Fahrenheit*</b> (used in USA)	°F	-523.67	32	212
<b>Kelvin</b> or <b>Absolute</b>	K (no ° used)	0	273.15	373.15

\* The Fahrenheit scale is rarely seen outside the USA and even more rarely used in any scientific applications.

4) If two objects of different temperature come into contact with each other, heat (but think *kinetic energy*) will naturally flow only from the warmer object to the cooler. They will reach a point where they have the same temperature (*kinetic energy*) and will be said to be in **thermal equilibrium**.

5) Heat exchanges between objects are never 100% efficient or complete, so it is believed that you cannot actually reach absolute zero in a finite number of exchanges.

## 10. Rotation and Equilibrium

Rotational motion involves moving in circles. We had an earlier glimpse of this when we looked at **circular motion**, but rotation is a bit different. Here is the difference: imagine there is a small merry-go-round at a park. If you were to run around its perimeter, you would be moving in circular motion. But if you stay where you are right now and *spin* around on one foot, you would be *rotating*. It turns out that rotation is just a special case of regular motion.

When we looked at simple motion we defined **speed** as the ratio of distance to time. In rotation we define **angular speed** as the ratio of **angular distance** to time. When a

rigid object rotates about an axis, every point on the object rotates with the same angular speed. Points farther out from the axis of rotation move with a faster *linear* speed. Angular distance can be measured using several different units, all based on the following equality:

$$1 \text{ rotation} = 360^\circ = 2\pi \text{ radians.}$$

Let's say you rotate slowly on one foot so that it takes you 4 seconds to make a complete rotation. Since we need to divide your angular distance by the time you took we can state your angular speed as:

$$1 \text{ rotation}/4 \text{ seconds} = 0.25 \text{ rps} \text{ "rps" is rotations or revolutions per second.}$$

(You will also find "rpm", revolutions per *minute*, as a unit.)

$$360^\circ/4 \text{ seconds} = 90^\circ/\text{s}$$

$$2\pi/4 \text{ seconds} = \pi/2 \text{ rad/s}$$

In a similar way, all of the other motion quantities we have encountered have rotational **analog**s. (When something is analogous to something else, it has a similar position or role. For example, in major league baseball the annual Cy Young Award (for pitching) is analogous to the Hank Aaron Award (for hitting).)

There is rotational (or **angular**) acceleration, work, kinetic energy, momentum, impulse, and the like. What makes them a bit different is that the quantities of *mass* and *force* that Newton introduced have to be replaced by two analogous quantities of **torque** and **moment of inertia**, also called **rotation inertia**.

Recall that it takes force to change the motion of an object. In the same way, it takes a *torque* to change the *rotational* motion of an object. Force is a part of torque, but there is more. To get an object to rotate you must exert a force on it, but that force is more effective in causing rotation if it is applied farther from the axis of rotation. A good example of this is opening a door on hinges. The hinges are the rotational axis. If you push on the door hinges, the door is *not* going to open (rotate). The farther away from the hinges that you push, the easier it is to open the door. This distance from the axis to where you apply the force is called the **lever arm**. In an equation,

$$\text{torque} = \text{force} \times \text{lever arm.}$$

With a large lever arm, a small force can actually exert a large torque. When you are trying to turn a screw or a bolt, you are rotating it. *Torque* is what you need. Wrenches with long handles provide a long lever arm and therefore a large torque.

The rotational analog to mass (rotational inertia or moment of inertia) also involves distance from the axis. The farther the mass of an object is from its axis, the harder it is to get rotating. The closest example you have is your own legs. When you walk, your thigh bone (femur) rotates in a ball-and-socket joint in your hip. Your leg has a certain amount of rotational inertia when it is stretched out straight. When you decide to walk faster or run, you will naturally bend our leg at the knee to do so. What this does is to move some of the mass of your leg closer to the rotational axis (hip joint) and reduces your leg's rotational inertia. This makes it easier to rotate (accelerate) your leg back and forth. The rotational inertia of an object is calculated using both the mass of an

object and the distance of that mass from the axis *squared*. So location of mass is actually more important than the amount of mass itself.

## 11. Equilibrium

Now that you have an idea as to what force and torque are, we can look at a special situation called **equilibrium**. Equilibrium exists for an object when there is no *net* force or torque on it. There may be many forces and torques acting on the object, but because both force and torque are *vectors*, they might add up to be zero. This means that there is no linear or rotational acceleration. An object will continue to do what it is doing. (Remember Newton's First Law!) Imagine you and a friend are each pushing on a desk in a classroom. If you each push with the same force and in opposite directions, the net force on the desk is zero. The desk will not accelerate. But, if you push on one edge of the desk and your friend on another, the desk may start to rotate. This is *not* equilibrium. But, if you each push along the exact same line, the torques you are producing will be equal and opposite. There will be no net torque, and the desk move anywhere.

When you are sitting or standing still, you are in equilibrium. The force of gravity pulling down on you is equal to the force of the chair or floor pushing up on you. That upward force doesn't *have* to be equal. If the chair or floor were too weak, you'd fall down. But let's assume you have a strong chair and floor. Imagine sliding slowly off the side of the chair. If you slide too far, you'll fall (actually, *rotate*) off the chair. This means there must have been a net torque on you. How did that happen? When we look at torques caused by gravity, we use a special point called an object's **center of mass** or **center of gravity**. (Here on earth they're basically the same.) Gravity pulls down on all parts of you, but because forces are vectors, we can pretend that gravity is acting just on your center of mass. If you manage to slide far enough off of your chair so that your center of mass is *off* of the chair, there will be a net torque on you. In this case both gravity and the chair exert torques, but they do *not* add up to zero.

When you are standing or walking, the situation is similar. You will be stable - in equilibrium - as long as your center of mass is above your support area. If your center of mass gets outside your support area - like leaning too far forward - you'll not be in equilibrium and will rotate (fall) down.

## 12. Fluids

The word **fluid** comes from a root word that means "to flow". Both gases and liquids flow, and they behave so similarly that we can study them together under the title of *fluids*. What distinguishes a fluid from a solid is that a fluid is viscous — it takes the shape of the container it is in. When you pour milk into a glass, it takes the shape of the glass. Solids, like a rock, don't change their shapes to fit a container. A difference between gases and liquids, though, is that when you put a gas into a container, it will expand until it completely fills the container. Gases don't have a definite volume like liquids.

Before we can look at the behavior of fluids, you must understand the concept of **density**. There are two types of density used in fluid study. First is the **mass density** which is defined as the amount of mass an object has per unit volume. Water, for example, has a density of 1 gram per cubic centimeter or 1,000 kg per cubic meter. **Weight density** is defined as the *weight* of an object per unit volume. Water has a weight density of 9800 newtons per cubic meter or 1 pound per pint. A gallon of water or milk - 8 pints - weighs 8 pounds.

Another important concept and quantity that you need to know is **pressure**. Pressure is defined as the amount of force applied per unit area. In the United States we still use an English unit of pounds per square inch (PSI). In the metric system, the unit is the newton per square meter, also called the **pascal** (abbreviated Pa). If you check your tire pressure with a gauge, chances are it will be marked in both PSI and kPa.

The behavior of fluids can be outlined using the various principles that apply to them. These are named for the person given credit for discovering them.

### 12.1 Archimedes Principle

The **Archimedes Principle** explains why some things sink and some things float when placed in a fluid. The principle states that there is a **buoyant force** on any object in a fluid, and the size of that force is equal to the weight of the fluid displaced by the object. Say a piece of metal has a density of 5 grams per cubic centimeter. If you place this piece of metal into water (density = 1 g/cm<sup>3</sup>) each cubic centimeter of the metal will displace 1 gram of water and therefore seem to weigh 1 gram less. Let's do a specific example. Let's drop a 10 gram piece of this same metal into water. Now 10 grams of this metal will have a volume of 2 cm<sup>3</sup>. (Density = mass/volume so volume = mass/density). This piece of metal will then displace 2 cm<sup>3</sup> of water and have a buoyant force up on it equal to that of 2 grams. So, this piece of metal will seem to have a mass of 8 (10 minus 2) grams while in water.

Humans (because we have a large water content in our bodies) have a density very close to that of water - usually just a bit less. As a result, when we get into water we seem almost weightless. In fact, the majority of people will float in water. How can a ship made of thousands of tons of iron float in water? The iron is shaped into thin panels making a shape that displaces tons of water with *air*. Air is very much less dense than water, so as long as the displaced weight is larger than the weight of the ship, it will float. If the ship gets a leak, the amount of water displaced goes down and so does the buoyant force! Once the buoyant force is less than the weight of the ship, it will sink.

### 12.2 Pascal's Principle

**Pascal's Principle** deals with fluids that are **enclosed** in a leak-proof container. Pascal learned that in an enclosed fluid, any pressure change made anywhere in the

fluid will be transmitted throughout the entire fluid. Since pressure is the amount of force per area, a small force over a small area can exert a large force over a large area. Car lifts in garages and the brakes on a car both operate using this principle. When you step on the brake pedal in a car, you push a small piston and increase pressure on the brake fluid. At the location of the brake, this small piston area is made into a large one, and a large braking force is applied to your car's wheels.

### 12.3 Bernoulli's Principle

**Bernoulli's Principle** deals with *moving* fluids. Bernoulli learned that the pressure in a fluid that is moving is lower than the same fluid at rest. This is important in *aerodynamics*. The shape of an airplane wings moves air faster over the top of the wing and slower along the bottom. This means more pressure (force) on the bottom than on the top of the wing. The resulting upward force is called **lift**. Likewise, the spoiler or wing on the back of a race car is an upside-down airplane wing. The result is a net force *down* on the spoiler and on the car, which helps keep the car on the road! For another example, put a drinking straw into a glass of water and blow across the top of the straw. If you blow hard enough the pressure on the top of the straw will drop enough to "suck" water up the straw.

### 12.4 Poiseuille's Equation

**Poiseuille's Equation** involves the flow of fluids in tubes or pipes or even blood vessels. It all centers around what volume of fluid you can get to flow through a tube per unit time. Some things increase the flow rate; others decrease it. Here is a brief chart and the effect of changing each quantity:

Increase this quantity:	Result on flow rate:	Comments:
length of tube	decrease proportionally	The longer the tube, the smaller the flow rate.
radius of tube	increase by the 4th power of the radius change	WOW! Double the radius of a tube and you'll get 16 times the flow rate!
pressure difference between ends of tube	increase proportionally	Logical! Push harder and more will flow.
viscosity* of fluid	decrease proportionally	Thicker fluids are harder to push through tubes.

\***viscosity** is how "thick" a fluid is. Honey is more viscous than water. Molasses is more viscous than honey.

Poiseuille's equation can be used to explain why it is not good to have a diet high in saturated fats and cholesterol. Consuming a lot of these causes layers of plaque to build up in your veins and arteries, reducing their size. If you look at the equation you can see that if you were to decrease the radius of a blood vessel to *half* its original



size, the amount of blood flow would become only 1/16 the original! (1/2 to the 4th power is 1/16) As a quick check here, see if you can work out that the flow rate difference between a 3/4" and 5/8" garden hose is actually two times!

### 13. Vibrations and Waves

The basis of all wave motion is something that is **vibrating**. Something that is vibrating is merely moving back and forth in the same place, repeating its motion. What is needed to get this vibration (or **periodic motion**) is a **restoring force**. A restoring force is one that *opposes* the motion of the thing vibrating. That means when the object goes one way, the force is in the opposite direction. A simple example is a swing at a park. When you swing *forward*, the component of gravity opposing you is *backward*. When you are in the backward half of your swing, the component of gravity is *forward*. That is all that is needed.

In all periodic motion, there are two quantities that resist each other.

One quantity is the **restoring factor** - this is how hard the system tries to get back to where it has no net force on it. (That point is called the **equilibrium position**.) Imagine a ball bobbing up and down on a spring. If we make the spring stiffer, it will exert a stronger force and speed things up. We say, in this example, that the **frequency** increases and the **period** decreases. (Frequency is how many bounces there are per unit time; period is how much time is needed for each bounce.)

The other quantity is the **inertia factor** - this is how sluggish the system is in getting back to the equilibrium position. In our spring-mass example, the *mass* of the bobbing ball would be the inertia factor. The more massive the object is, the smaller its frequency and the longer its period.

A **wave** is a disturbance in a medium that transmits energy with no net movement of mass. If you want to make waves all you need is something that is vibrating and a **medium** to carry the wave. A medium is some sort of material (It can be a solid, liquid, or a gas.) that is **resilient** - that is, if you disturb it, it will try to go back to where it was. An example of a good medium would be a big chunk of Jell-O. If you poke it (disturb it) it will wobble - that's a wave. An example of an inefficient medium would be a bowl of oatmeal or grits - poke it and nothing happens. A good medium has a springiness to it.

You've seen many waves - perhaps water waves are the easiest to see - and their anatomy is quite simple. The highest point on a wave is called the **crest**. The lowest point is called the **trough**. These points are often equally above and below the equilibrium position, though they don't have to be. The crest-to-crest distance (or it could be trough-to-trough) is called the **wavelength**. The **amplitude** of a wave is the distance from a crest (or trough) to the equilibrium position. The crest-to-trough distance is called the **wave height**. You won't find wave height a common measurement in physics, but when they talk about wave heights on Lake Michigan during a weather broadcast, this is what they are talking about.

## 13.1 Properties of Waves

A body of water makes an excellent medium for waves because of gravity's quick response to return the water to a smooth, level surface. If you have a cup or bowl of water and you poke your finger into it, you'll see a wave (or waves) move out away from the disturbance you made. This is an example of one of the five characteristics of wave motion - **1. propagation**. To *propagate* something is to make another one. We propagate plants by planting seeds or making a cutting take root. A wave propagates in that after you make the first one, it continues to move and create a new disturbance in the direction the wave is traveling. The other four wave characteristics are: **reflection, refraction, diffraction and interference**.

**2. Reflection** occurs when a wave encounters the end of its medium. If you dip your finger into a bowl of water, the wave you made will speed out to the edge of the bowl, reflect off the edge and travel back. If you attach a long rope to a pole and give the rope a snap, the waves will travel to the pole and then reflect back toward you. This is like an echo. If you've ever heard an **echo**, you've heard the result of a reflection of sound waves.

**3. Refraction** occurs when a wave moves from one medium to another. We'll do more with this when we get to light waves, but when a wave moves to a new medium it will change speed and usually change direction. This bending is called refraction.

**4.** Waves have the special property of being able to spread out after encountering an opening or the edge of a barrier in the medium. This spreading is called **diffraction**. All waves will diffract after an opening or barrier edge. What is important to remember is that the longer the **wavelength** of the wave, the more it will diffract. An example of diffraction you might have heard is that of sound waves coming from a stereo whose speakers you can't see. If you can't see the speakers, then the sound that got to you must have bent around corners and gone through openings. What sounds do you usually hear in this case? The "bass" or "low notes." Low pitch in sound and music corresponds to long wavelength. Low bass notes diffract better than high notes that have a small wavelength.

**5.** You are well aware that you can't put two baseballs in the same place at the same time. Waves are special in that you *can* put two (or two hundred!) waves in the same place at the same time. Since waves are actually just an energy-carrying disturbance, you can have as many as you want in the same place. When this occurs we say that the waves experience **interference**. There is only *one* medium, so we will see only *one* wave, and it will be the *sum* of all the waves trying to occupy that space. The **Principle of Superposition** is a rule that says when multiple waves hit that same place at the same time, you'll see one wave that is the simple sum of the individual waves. To simplify, imagine just two water waves - each one inch high - colliding with each other in a bathtub or swimming pool. When they meet, each wants to be 1 inch tall. What you will see - for an instant - is a wave that is 2 inches tall. That is, if the two *crests* meet. But, if a 1 inch *crest* meets a 1 inch *trough*, the sum of the waves is zero

and they will instantaneously cancel. Here 1 plus -1 equals zero. But the waves don't disappear forever! They continue moving right through each other and emerge from the collision unharmed — that is, even though at their meeting place the water is flat, you'll see that the crest and the trough will reemerge from the meeting and continue travelling along their respective paths. Only waves can do this.

### 13.2 Types of Waves and Their Characteristics

Of the various **mechanical waves** you run into everyday, most can be placed into two main categories **transverse** (sideways) waves and **longitudinal** (compressional) waves. When you pluck a guitar string it vibrates back-and-forth transversely, and the vibrating is called a transverse wave. But as the guitar string slaps back and forth against the air, the sound wave it makes in the air is a longitudinal wave. The guitar string alternately compresses and rarifies the air around the string. This wave propagates out in the air as **sound** if the frequency is between about 20 hertz and 20,000 hertz. Frequencies below 20 Hz are called **infrasound**. (Elephants use frequencies in this range.) Frequencies above 20,000 Hz are called **ultrasound**. (Dogs can hear into this range. Some insects and bats do all their communicating in this range.)

The unit **hertz** is the number of vibrations or waves *per second*. A guitar string vibrating back and forth 50 times per second will make a sound wave with a frequency of 50 Hz. The frequency range of 20 to 20,000 Hz for sound is based on what a young, healthy human can hear. As we grow older, especially in noisy urban environments, our range of hearing decreases. Older people cannot hear higher frequencies as well as younger people. Long exposure to loud sounds reduces the frequency range we can hear. Unfortunately, it turns out that technology has sped up the process of hearing loss. You no longer have to work many years in a loud factory to experience high frequency hearing loss. The use of portable stereos with headphones and loud car stereos has accelerated the hearing loss of young people.

We can measure sound loudness (or intensity) using the amount of power a sound wave delivers to a certain area. There is a minimum sound intensity that is required to activate the normal human ear. It's incredibly small - a millionth of a millionth of a watt per square meter. Our ear drums are incredibly resilient - it takes more than one watt per square meter to instantly damage our ears. The range of human hearing - intensity-wise - is so great that a logarithmic scale was invented to cover the range. This is the **decibel scale**. The softest sound you can hear (called the **threshold of hearing**) is given a value of 0 dB. A quiet two-person conversation has a rating of about 60 dB. Every ten dB is a tenfold increase in the intensity. A 20 dB increase is 100 times. 30 dB is 1,000 times. Sounds greater than 80 dB can endanger human hearing. It is a combination of both intensity and time (called **duration**) that is dangerous. Some rock concerts can have sound levels from 100-120 dB. Although those levels are damaging, an occasional concertgoer will not experience anything near the damage experienced by a musician who practices and plays many hours at that level.

To review, sound waves exhibit five wave behaviors: 1) they **propagate** in moving out from their source; 2) they **reflect** - consider echoes; 3) they **refract** - listen to planes overhead on a really cold day; 4) they **diffract** listen to the bass of your friend's sound system, and; 5) they **interfere** - listen to a choir and then a soloist.

## 14. Electrostatics

At this point you may need to flip-flop between the chemistry and physics parts of this narrative. To understand electrostatics you must have a visual model of what an atom looks like. We can't see atoms directly - they're too small. But through many other experiments we have evolved a model of what an atom looks like. Most of an atom is nothing - just empty space. At the center we imagine an incredibly small, super dense bundle of mass (called the **nucleus**); and at an incredibly distant point (relatively speaking) we find a sort of beehive swarm of flimsy particles with almost negligible mass - the **electrons**. The force that holds an atom together is called the **electric force**.

The force of gravity acts between any two objects that have *mass*. The electric force requires that the objects possess something called **charge**. We actually don't know what charge *is*, but we know a lot about it. It comes in two forms (we call them *positive* and *negative* after work done by Benjamin Franklin). We know the following:

- like charges repel;
- opposite charges attract;
- the more the charge, the stronger the force;
- the farther apart the charges are, the weaker the force by an *inverse square* relationship. That is, *double* the distance between two charges and the force will drop to one *quarter* of its original value.

Physicists have a sense that the net charge in our universe is zero, or at least constant. That means for every positive charge you find, there is a negative one somewhere. And *where* that other charge is is usually *very close*. Compared to gravity, electric force is almost incomprehensibly strong. As a result, if charges in atoms get separated somehow, it usually isn't very long before they get together again. Result: most objects you will encounter are **neutral**, meaning they have equal numbers of positive and negative charge. Most of the time a human is neutral in charge. But on a cold, dry winter day if you scuff your shoes across a carpet or rug, you might take on a net charge because you scraped off negative charges from the carpet fibers. In such a case you have more negative charges than positive. If you now contact something (a door knob, a light switch, the back of your friend's neck) with less charge than you, you might transfer that charge over to them. It happens quickly and generates a small **spark**. Sparks are just miniature lightning bolts where the energy of the separated charges gets turned into momentary heat energy (the blue spark and sound). The lightning and thunder associated with weather events is just the same event on a much larger scale.

You can't make a net charge - nature keeps a balance. However, you can separate charges as we just saw. When charges get separated they possess potential energy (It took work to separate them!). We can use that potential energy at a later time. However, this **electrostatic potential energy** is very difficult to control and use. Fortunately, 200 years ago an Italian scientist, Alessandro Volta, discovered a chemical means to separate charge. He invented the battery. It was one of the most important discoveries ever because it gave a controlled way to use electric energy. Later, generators, solar cells, and more exotic means would be discovered.

With the invention of the battery came the creation of **electric circuits**. An electric circuit consists of some source of electric potential energy, some device that will convert that energy into some other form (heat, light, sound, motion), and connecting paths between those two - most commonly, wires. The root word for circuit is the same as for circle. There must be a complete loop from the battery through the energy converting device and back again for the circuit to operate. What carries the energy through a circuit are the tiny electrons from each atom in the conducting path.

Metal wires are usually used for completing the circuits because one or more electrons in each metal atom is very loosely held by the atom's nucleus. These loose electrons give metals their unique properties of heat and electrical conduction, luster, and malleability (non-brittleness). See more about this in the Chemistry section on metals.

Quantities that we can measure in an electrical circuit are outlined as follows:

Quantity	Unit	Abbrev.	Symbol in equations	Comments
quantity of charge	coulomb	C	Q	This is an arbitrary, large number of charges ( $6.25 \times 10^{18}$ of them)
potential	volt	V	V	1 V = 1 J/C
current	ampere	A	I	1 A = 1 C/s
resistance	ohm		R	1 $\Omega$ = 1 V/A
power	watt	W	P	1 W = 1 J/s

A German scientist, Georg Ohm, was the first to discover that the amount of current you get in a circuit is usually directly proportional to how much potential (or you can say "voltage") is applied. Potential is very much like pressure (recall Poiseuille's equation) so it is logical that more voltage produces more current. But conductors are not perfect, so they end up providing what is called resistance. The more resistance in a circuit, the less current you will get. This relationship can be represented in an equation:

$$I = V/R$$

It is more often written as  $V = I \times R$  and is called **Ohm's Law**.

The power used in a circuit can be calculated in several different ways, all equivalent. You can use

$$P = V \times I$$

$$P = V^2 / R$$

$$P = I^2 \times R$$

depending on what information you happen to know.

When you investigate circuits further, you'll discover that most circuits have more than one device that provide resistance. These may end up being placed end-to-end (in "series") or side-by-side (in "parallel"). When resistors are wired in **series**, their resistance simply adds up. So the equivalent resistance of a 4 ohm and 5 ohm resistor in series would be 9 ohms. Resistors wired in **parallel**, though, make it easier for the current to flow because there are now multiple paths for the current. The calculation of the equivalent resistance for parallel resistors is much more complicated and requires using the reciprocal of the sum of the reciprocals. For our 4 and 5 ohm resistors this becomes:

$$R = 1 / (1/4 + 1/5) = 1 / 0.45 = 2.22 \text{ ohms.}$$

Most modern circuits are very complex combinations of resistors in patterns that can eventually be analyzed using these two simple combinations - series and parallel. In addition, you will find components like **capacitors** which temporarily store electrical energy and charge. As you can see, electronics can get complicated. But the next time you listen to recorded music, use the telephone, or sit down at a computer, be aware that charges flowing through these complicated circuits are doing work for you!

## 15. Magnetism

The field of **magnetism** developed completely separately from electricity for at least two thousand years. The name magnetism comes from the place name in Asia Minor of *Magnesia* - where magic rocks were found that could attract pieces of iron metal. We call these natural magnets **lodestones**. It turns out that these rocks are really not very rare. In fact, one form of iron ore - magnetite - is mined for the production of iron and steel.

Early in the history of magnetism it was noted that every magnet seems to have two very strong areas of attraction (these are called poles) and, just like electric charges:

- like poles repel
- opposite poles attract
- the more magnetic material, the stronger the force
- the farther apart the poles are, the weaker the force by an *inverse square* relationship. That is, *double* the distance between two poles and the

force will drop to one *quarter* of its original value.

In addition, it was known that a magnet free to move in any direction would eventually line up with one pole facing north and the other south. The magnetic poles were named, then, north and south. But then is the earth itself like a magnet? Of course! It has strong centers of magnetic effect near the north and south geographic poles. But, since the decision was made to name the pole of a magnet that faces north, the “north-seeking pole”, that means the earth’s magnetic pole that is near geographic north must be a *south* magnetic pole. Geologic evidence shows that the earth’s magnetic poles are not constant in magnitude, location, or type. The poles wander, disappear, and reappear in the opposite direction over very long periods of time. It doesn’t seem to have a periodic pattern (Our sun has a very regular 22-year cycle of magnetic changes.) and we don’t have an explanation for this cycle. The earth’s magnetic field is actually very valuable for us because it traps high energy particles that bombard us from the sun and outer space. These trapped particles make up what are called the **Van Allen Radiation Belts**.

These radiation belts are evidence that electricity and magnetism are somehow related. This connection was actually made accidentally by Hans Christian Oersted in 1820 when he noticed an electric circuit he was working with deflected the needle on a nearby compass. This chance discovery led to rapid progress in both electricity and magnetism. We now know that the source of all magnetism is moving electric charges. Moving charges in atoms accounts for the magnetic effects of iron, aluminum, cobalt, and other metals. Simply running an electric current through a piece of wire in a circuit will generate a magnetic field. Put that piece of wire in a preexisting magnetic field and the field of the wire will interact with the original field. If you arrange things properly, you can make an **electric motor**. Detach the battery from an electric motor and simply spin the motor - you’ll find that the motor generates a voltage. Hence we call it a **generator**.

We in the United States use a tremendous amount of energy, and we have it delivered in two basic forms. The first, gasoline and diesel fuel, we use by burning in internal combustion engines in our cars, truck, lawnmowers, and the like. The second, electricity, is made by simply rotating coils of wire (admittedly *big* ones) in magnetic fields. The energy needed to rotate these coils may come from water turbines below dams or steam turbines powered by burning coal, oil, or by splitting uranium atoms. In all cases, **electromagnetic induction**, as it is called, produces the convenient form of energy we simply call electricity.

## 16. Electromagnetic Waves and Light

We’ve seen earlier that you can make waves in a physical medium by simply vibrating something in the medium. It turns out that if you vibrate an electric charge like an electron, it also makes a wave. These waves have a couple of unique properties. First, they don’t need a medium! They sort of make their own because the vibrating charge makes a magnetic field that in turn makes an electric field which in turn makes a

magnetic field - ad infinitum! Second, these waves travel at the amazing speed of 300 million meters per second. (That's about 186,000 miles per second.)

Most of these waves are invisible to us with the exception of a small range of frequencies. Remember that for us to detect compressional waves (sound) they must be in the range of 20-20,000 Hz. Likewise, if we can get electromagnetic waves in the range of  $10^{14}$  to  $10^{15}$  Hz we humans can detect them. Electromagnetic waves from about 4 to  $7.5 \times 10^{14}$  Hz excite nerves in our eyes' retinas and we see **light**. The lowest frequency we can see is *red*. The highest frequency we can see is *violet*. The **visible spectrum** has the identifiable colors of red, orange, yellow, green, blue and violet. ROYGBV is a clever way to remember them. It is important to remember that it is a continuous spectrum: red doesn't suddenly switch to orange, etc.

Just like we noted **infrasound** and **ultrasound** were wave frequencies we couldn't quite hear, there are **infrared light** and **ultraviolet light** which we can't see. However, we can detect these. If you've ever walked past a hot stove or a hot radiator and "felt" the heat radiating from them, you've detected infrared light. It takes our bodies longer to detect ultraviolet light because our body's response is to generate more of the skin pigment *melanin*. This is the tanning reaction the skin has in response to the **UV rays** (another name for these frequencies). It seems to be a protection mechanism or sorts, because too much ultraviolet radiation can result in the development of skin cancers. Not all UV is bad because vitamin D is also formed as a result of the rays. Vitamin D is sometimes called the *sunshine vitamin*. But too much vitamin D is not a good thing. One theory suggests that the natural variation in skin color with latitude (darker skin at low latitudes, lighter skin at high latitudes) is somehow connected to how much vitamin D production is needed. At high latitudes (Scandinavia, for example) sunlight is simply not in abundance. Very little melanin means more of the sunlight can be used for vitamin D production. In the low latitude tropics, darker skin color seems to serve as protection against overproduction of vitamin D.

## 16.2 Behavior of Light

When we investigate visible light, we find that it exhibits the five elements of wave behavior that we studied before:

1. When light **propagates**, it (usually) spreads out in all directions from its source. It is actually made of little bundles called photons, but acting together they look like waves. They travel in a vacuum at  $3 \times 10^8$  m/s - this is as fast as light can ever travel.
2. When there is an abrupt change in its medium, light will **reflect**. It follows a simple rule of reflection that can be summarized with the phrase, "Angle *in* equals angle *out*." If a **ray of light** (an imagined tiny bit of a light wave) strikes a mirror or piece of glass at, say,  $10^\circ$ , it will reflect at that same  $10^\circ$  angle.
3. When light moves from one **transparent** medium to another, it may slow down or



speed up. When it does this, the rays of light will bend. This is called **refraction**. Refraction causes swimming pools to look shallower than they really are. Refraction is the reason why pencils may look bent if you dip them in a glass of water. Eyeglasses, prisms, and other transparent objects seem to distort images we see through them. These are all examples of refraction. There is a mathematical relation between the light speeds and amount of bending called **Snell's Law**. We don't need the details of it here, but keep your eyes open for it when you study more physics.

4. Because light has such high frequencies and short wavelengths, we don't normally get to see **diffraction** examples. However, if you've ever seen a hologram (a two dimensional image that looks three dimensional) you've seen diffraction.

5. The **interference** of light is also not so commonplace. But if you've ever seen bright colors in small oil spills in a parking lot after a rain storm, or if you've seen the iridescent colors on seashells or butterfly wings, then you've seen light interference.

## 17. Modern Physics: Relativity & Quantum Mechanics

Everything we've looked at so far is often called **classical physics**. It is physics that we can find in our every day lives. However, during the late 19th and early 20th century physicists began looking at smaller and smaller details. They began to find results that border on science fiction. These new areas of physics can loosely be called **modern physics**.

One of the more startling discoveries was made by Albert Einstein and was published in his **Special Theory of Relativity**. This theory deals with observations made by different people moving at different speeds (constant speeds - no acceleration allowed). It turns out that measurements of time, distance, speed, mass, and momentum are affected by the relative motion of the object being measured and the person measuring it. Strange! To make a very long story very short, here are some predictions made by the theory, all of which have been verified:

First imagine that we have the universe's fastest, sleekest sports car in front of us *at rest*. We get out our instruments and measure its length, its mass, we synchronize its clock with our clock. Now we have its driver drive past us at an incredibly fast speed (less than the speed of light, though!). We again measure the car - this time while its moving. We will find these results:

- the car will seem to have more mass than it did at rest
- the car will seem to be shorter in the direction it is moving than it was at rest
- the car's clock will be slower than ours.

Strange, but true.

Now at actual sports car speeds you won't find a detectable change, but when tiny particles are accelerated to speeds that are a significant fraction of the speed of light, the changes do occur exactly according to Einstein's predictions. A premise of the Special Theory that all observers will measure the speed of light to be the same (3 X

$10^8$  m/s) has also been verified. In addition, that extra mass that we found when the car zoomed past us can be calculated using the famous  $E = mc^2$  equation.  $E$  is the car's kinetic energy,  $c$  is the speed of light, and  $m$  would be the additional mass we found.

Einstein's General Theory of Relativity is one of the most mathematically challenging ideas in existence. A small handful of physicists truly understand it in its entirety. Unlike the Special Theory which dealt with non-accelerating object, the General Theory deals with accelerations. A premise that you should remember is that it is impossible to distinguish between what we call "gravity" and the acceleration caused by it. Sounds like gibberish, but it suggests that large masses like the earth and the sun distort empty space and curve it. So if we decide to jump off a diving board into a swimming pool, we can explain it classically: gravity exerts a net force on us, so we accelerate down to the water. OR we can use the ideas of the General Theory and imagine we're sliding down a curved portion of the space-time continuum.

When dealing with incredibly tiny particles and attempting to investigate them, we run into another problem - the measuring process will affect what we are trying to measure. A simple analogy is this: if you want to know what your body temperature is you simply put a thermometer in your mouth and wait until the mercury in it has stopped expanding. When the thermometer and you are at the same temperature, heat flow will stop. You lost a negligible amount of heat energy to the thermometer. Now, imagine using the same thermometer to measure the temperature of a drop of water. The heat energy from the drop of water will transfer to the thermometer and expand the mercury. The expansion will stop when the drop and the thermometer are at the same temperature. But this time the drop of water will have lost a significant amount of heat energy so the reading on the thermometer can't be the original temperature of the drop. Frustrating! However, quantum mechanics deals with just these problems. Be advised, though, the result is a tiny universe that is a little hazy and a little fuzzy!

A perplexing problem physicists had in the early 20th century was that under certain conditions light behaved like a wave (We've seen that.) but at other times it more resembled a particle. Well, what is it? This idea became known as the wave-particle duality and physicists had to deal with it. It was frustrating. Then the Danish physicist Niels Bohr proposed what is called the **principle of complementarity** which states that to understand any single experiment you must choose either the wave model or the particle model of light. You can't use both at the same time. You can't even imagine something that is both wave and particle, though a few have tried to float the idea of a **waveicle**. It didn't fly.

Another aspect of all this uncertainty is called the **Heisenberg uncertainty principle**. This principle states that the certainty with which you want to know one quantity may lead to a greater uncertainty in another. The two pairs of quantities are **position** and **momentum** and **energy** and **time**. Very simply, if you really want to know the position of a small particle accurately, your ability to measure its momentum (and therefore be able to predict its future whereabouts) will decrease. With energy and time, we have a similar problem. As we try to measure energy changes of a

particle, the smaller a time we try to focus on, the larger our uncertainty in the energy measurement becomes.

The nice thing about all of this modern physics is that it applies, as far as you and I are concerned, with very small scenarios in sub-microscopic worlds. We can concern ourselves with it when we're in the mood to, but everyday life can go on oblivious to these strange goings-on!

## 18. Nuclear Physics

Very small scale physics that does or can affect us on a daily basis is the study of the nucleus of atoms. We'll look at this more in the following chemistry section of this booklet, but for the moment here is a problem regarding an atom's nucleus: knowing the physics that we have learned so far, nuclei larger than hydrogen shouldn't exist. The repulsive force between the positively charged protons is so great when they are compacted so close together, that the nucleus just shouldn't stay together. It should fly apart!

But, we haven't yet looked at the **strong nuclear force** in any detail. This is an incredibly strong (pun intended) force that exists between **hadrons**. Hadrons are a family of subatomic particles that includes protons and neutrons in addition to many other particles with names such as pions and kaons. At very small distances, hadrons are attracted with this strong force that overpowers the repulsive electric force and helps keep the nucleus together. Since all hadrons attract and only the protons in a nucleus repel, you can think of the neutrons as being like a glue that keeps the nucleus together. You'll see later in this booklet that large atomic nuclei aren't very stable. That is because as you make a larger and larger nucleus, the protons find themselves farther away from each other than the strong force can reach, and there simply isn't enough glue to hold it together. When this large nucleus breaks apart, a process called **fission**, the debris will be two or more fragments of the original nucleus. Some individual neutrons might also be ejected. Electromagnetic waves (called **gamma rays**) can result as well as electrons. Splitting any nucleus larger than iron will result in large amounts of energy being produced. This energy, by the way, is a direct result of the debris having less mass than the original nucleus. Using the equation  $E = mc^2$  will allow calculation of the amount of energy produced.

Splitting nuclei smaller than iron requires more energy than it releases. However, *combining* smaller nuclei, a process called **fusion**, results in a net energy release. A dream of physicists is to be able to combine hydrogen nuclei to make helium and release large amounts of energy. This is the same reaction that goes on in our sun and most of the other stars. The byproduct, helium, is a nontoxic, inert gas. The promise of nuclear fusion to provide our electrical power in the future is an exciting one.

It turns out that our "elementary" protons and neutrons aren't really elementary. Our current model of the subatomic universe shows protons and neutron as being composed of smaller particles called **quarks**. The **standard model** of these particles

has six different quarks, in three paired sub groups. These pairs are: **up** and **down**; **strange** and **charmed**, and; **top** and **bottom**. Our model has the proton made from two *up* and one *down* quark. (The charge on an up quark equals  $+2/3 e$ , and the down quark has  $-1/3 e$ . As a result the proton can be represented as  $2/3 e + 2/3 e - 1/3 e = 1 e$  !!!) Our neutron model should therefore have *one* up quark and *two* down quarks. Try to figure out why the neutron would have no net charge. When you add to this model another set of particles that has six **leptons** (the electron is one of the leptons), physicists can construct most of the universe from these few particles. By the way, each of these particles has an **anti-particle**, so there is much not covered by the standard model.

## 19. Cosmology

In the last two sections of this booklet we looked at the very smallest entities in the universe. Cosmology is the extreme opposite. Cosmology looks at the universe as a whole and attempts to make sense out of its past, its present, and its future. You'll find most of the astronomy details in the Earth/Space/Environmental Science booklet, so here we'll simply look at the prevailing view of the history of our universe.

Experimental evidence suggests that our universe is expanding. It is as if there had been a large explosion and the matter we see (stars, galaxies) is debris flying out in all directions. Most evidence points to this explosion, called the **Big Bang**, occurring some 10-15 billion years ago. Physicists have a model called the **standard model** that tracks what might have happened to get us from that Big Bang to the present. In the first few seconds of the Big Bang the universe went from a pure energy state to the formation of hadrons (including protons and neutrons) and leptons (including electrons). From then through about a third of a million years (called the **radiation-dominated era**), hydrogen and helium nuclei formed. At this point the universe had cooled enough that gravity began to work its magic in forming stars and galaxies. We're in that era today, called the **matter-dominated era**. From time zero, when the temperature of the universe was in the neighborhood of  $10^{32}$  kelvin, we have cooled to a chilly 3 kelvin. This temperature of three degrees above absolute zero is measured by looking at what is called **cosmic microwave background radiation**. This radiation is the smoking gun of the Big Bang — that is, evidence suggesting its having happened.

Where are we headed? The continued expansion of the universe will lead to more and more cooling, for sure. But, will we: continue to expand forever; expand more slowly and just stop, or; will the expansion cease and then everything just collapse back into what is called (for obvious reasons) the **Big Crunch**? As of this writing there are strong suggestions that the second scenario might be the fate of our universe.

However, the current missing piece of the puzzle is a number that is called the **mass density** of the universe. If it is above a certain value called the **critical density**, we'll get a Big Crunch. If it is below that value, we'll expand forever. Why can't we tell for sure? Physicists have evidence for something called **dark matter**. It can't be seen like stars and galaxies and it only reacts using the **weak nuclear force**, so it is very elusive. But, if there is enough of it in the universe, we'll Crunch. An interesting

outcome of that scenario is that it suggests the universe itself is **cyclic**, like so many other things *in* the universe. That could mean that the universe has been around for much longer than 10-15 billion years. How many cycles has the universe gone through? And for how long? Unfortunately, that question can't be answered yet, if ever.

However, calculations have been done on the formation and evolution of our universe with slight changes in the values of some of the fundamental constants. The surprising result is that the predicted universe would look nothing like ours today, and life as we know it would not be possible. Called the **Anthropic principle**, it suggests that somehow this universe was custom made for us. Whether we are flattering ourselves with this theory is, of course, open to debate...

## II. CHEMISTRY

We'll now take some of the physics we have learned and apply it to the study of chemistry. If you truly understand some of the concepts we've covered – especially electrostatics, energy, and momentum – you'll find chemistry quite easy. Remember our model of the atom: a dense, massive nucleus surrounded by light, energetic electrons with lots of empty space in between. Chemistry is the study of what goes on when the nucleus and electrons from one atom interact with those of one or more other atoms. Although we'll take another look inside the nucleus, the **electric force** is the one we almost exclusively deal with in chemistry. It not only holds an atom together, but it holds atoms together to make **molecules** which are collections of two or more atoms.

### 1. Units and Measurement

We briefly met the **mole** in our physics section, but in chemistry we'll use the unit extensively. A mole of anything is a particular number of atoms or molecules. You know that a **dozen** of anything is 12. A **gross** of anything is 144. A **mole** of anything is  $6.02 \times 10^{23}$  of that thing. It's a huge number, but remember that atoms are incredibly small, so a mole of atoms may not actually weigh all that much. In fact, if you take the simplest atom there is, hydrogen, and collect a mole of its atoms, it will weigh exactly one gram. Since all other atoms are larger and more massive than hydrogen, it makes a good unit for measuring quantities of atoms. We'll need our units of temperature and energy later, so be sure to review those.

### 2. Matter and Energy

Sometimes chemistry is referred to as the study of matter and energy. Indeed, matter is what we are looking at. The ancient Greeks thought that everything in the universe had a smallest part. That is, if you take a rock or a drop of water and keep dividing it in half, eventually you would get to a point where you couldn't divide it anymore and still have what you started with. What amazing foresight!

Our current model in chemistry is exactly that. If you take a drop of water and look for a smallest piece, you'll have what we call a **molecule** of water. That molecule *can* be divided further, but after you divide it, you no longer have water. You have hydrogen and oxygen. Suppose we were to take everything on earth and start chopping. When we were all done, we'd come to an extraordinary discovery: a set of only 88 building blocks. These are called **elements** and they come in great variety. There are solids, liquids, and gases. They range from white to black to shiny to dull. They have properties that we can measure. These properties are usually divided into two types:

1) **Physical properties** are those quantities we can measure *without* having the element combine or react with other elements. These would include **density**, **melting point**, **boiling point**, **specific heat**, and the like.

2) **Chemical properties** are those that involve reactions with other elements.

For example, burning in oxygen or reacting with certain types of gases.

Although our earth contains only 88 different elements, scientists have put together an additional 24 in the laboratory. Unfortunately, these 24 have nuclei that are not stable, so they quickly disintegrate. That, by the way, is why we don't have them naturally on earth in the first place!

When atoms of elements combine *chemically*, we say they make molecules. It's possible to combine some atoms of the same element. The result is called a molecule, but it is still the same element. The common gases hydrogen, oxygen, and nitrogen occur in nature as **diatomic** molecules ("two" atoms). But when different elements combine chemically, the result is usually very different from the original elements. These new molecules are called **compounds**. A compound is made up of two or more elements. If you combine hydrogen and oxygen gas by burning, the result is water...a totally different substance!

If you mix elements or compounds together *physically*, not allowing a chemical reaction, you get what is called a **mixture**. Mixtures can be separated by physical means. These mixtures are usually categorized as either **heterogeneous** or **homogeneous**. In a heterogeneous mixture, the components are obviously separate and different. If you mix the two liquids oil and water, the oil will float on the top and the water will stay below. If you mix sand and water, same thing. In a **homogeneous** mixture, the different components are not so easy to see. Two types of homogeneous mixtures are **solutions** and **alloys**. Common table salt will dissolve in water, leaving a mixture with a uniform composition. But this isn't an example of a chemical reaction, since we still have salt and water. Let the mixture stand for a while and the water will evaporate, leaving you with your original salt. Melt copper and zinc together and you will form the alloy **brass**. The two metals can be separated physically, so this is still a mixture, but its composition is uniform - homogeneous.

### 3. Atomic Structure

We know that our universe has at least 88 (or 112) elemental building blocks called **elements**. What if we were to break apart one of these elemental atoms? It turns out that no matter which element you pick, you'll find only three types of particles inside it. We've already met them: the proton, the neutron, and the electron. Here is how they compare:

Name	Symbol	Mass	Charge
proton	p <sup>+</sup>	1.6726 X 10 <sup>-27</sup> kg	+e <sup>*</sup>
neutron	n <sup>0</sup>	1.6749 X 10 <sup>-27</sup> kg	0
electron	e <sup>-</sup>	9.11 X 10 <sup>-31</sup> kg	-e <sup>*</sup>

\* The charge on a proton or electron is the smallest found in nature. All other charges are an integer multiple of this value, 1.6 X 10<sup>-19</sup> coulomb. It is used so frequently that the letter "e" is assumed to be this

value in this context. Special note, the *size* of the charge on the proton and electron are the same to at least 22 decimal places! Physicists are pretty sure they are “equal.”

It turns out that what makes an element unique is its number of protons in the nucleus. That’s it! We saw earlier that neutrons are a sort of glue in a nucleus. What gives a particular element its special characteristics is its number of protons. If a nucleus has one proton, it can only be hydrogen. You can actually make a hydrogen that contains one proton and one neutron. It’s twice as heavy, but it still acts like hydrogen. Add a second neutron and it’s three times as heavy, but still hydrogen. These different forms of the same element are called **isotopes**. They are chemically the same, but may have other properties like an unstable nucleus (radioactive). Below is a chart of those hydrogen isotopes as a summary:

Name	Symbol	Protons	Neutrons	Atomic number	Mass number
hydrogen	H or ${}^1_1\text{H}$	1	0	1	1
deuterium	D or ${}^2_1\text{H}$	1	1	1	2
tritium	T or ${}^3_1\text{H}$	1	2	1	3

The quantities of **atomic number** (abbreviated with **Z**) and **mass number** (abbreviated with **A**) have been introduced here. The atomic number is just the number of protons in the nucleus, which determines which element it is. The mass number is the number of **nucleons** (protons + neutrons) in the nucleus. Obviously, if you want the number of neutrons, take the difference. In some charts you’ll find non-integer values for the mass number, also called **molar mass**. You can’t have part of a neutron in a nucleus. When you see a decimal value, it is an *average* value of the various isotopes found on earth.

In the same way that you can’t master a new language without learning a lot of new words, it’s hard to learn chemistry without learning the names of the elements *and* their chemical symbols. In the same way mathematicians use symbols like + and - to represent operations, chemists use symbols to represent the names of the elements. It is nothing more than shorthand! The chemical symbol will consist of one or two letters. The first is always capitalized; the second is never capitalized. (If you find two adjacent capital letters, it is two separate elements. **Co** is the symbol for cobalt. **CO** is the molecule carbon monoxide.) The majority will seem quite logical. Here are a quick dozen to get you started:



<b>Name</b>	<b>Symbol</b>
hydrogen	H
helium	He
lithium	Li
boron	B
oxygen	O
nitrogen	N
neon	Ne
carbon	C
cobalt	Co
calcium	Ca
chlorine	Cl
aluminum	Al

Here is almost a dozen whose chemical symbols aren't as obvious because they were derived from an earlier Latin name for the element:

<b>Name</b>	<b>Symbol</b>	<b>Former name</b>
antimony	Sb	stibium
copper	Cu	cuprum
gold	Au	aurum
iron	Fe	ferrum
lead	Pb	plumbum
mercury	Hg	hydragyrum
potassium	K	kalium
silver	Ag	argentum
sodium	Na	natrium
tin	Sn	stannum
tungsten	W	wolfram

It is also possible for an atom to lose or gain electrons. This has no effect on which

element it is. When the number of protons and electrons in an atom is equal, we say it is **neutral**. An atom with a different number of electrons it is called an **ion**. An atom that has lost one or more electrons would have a net positive charge and is called a **cation** (pronounced *CAT ion*). An atom that has gained electrons would have a net negative charge and is called an **anion** (pronounced *AN ion*). Different elements have different tendencies to gain or lose electrons and this is the heart of chemistry. How an element shares (or refuses to share) electrons with other elements is what it is all about.

#### 4. Electron Configuration and the Periodic Table

You probably understand by now that the *electrons* in atoms will be a major player in how they will react with other atoms. We owe thanks to Dimitri Mendeleev (1869) and Lothar Meyer (1870), Russian and German chemists who independently came to the conclusion that there was something periodic (repeating) about the physical and chemical properties of elements when you list them in order of increasing mass. There was a beautiful pattern! It was a bit strange. Numbers like 2, 6, 10, and 14 dominated in the pattern. Nature seemed to have a plan in making elements.

In our look at Modern Physics, we skipped an idea called the **Pauli Exclusion Principle**. Its main premise is that there are certain characteristics that electrons have when in an atom (quantities like **spin, angular momentum**, and the like.) From these quantities (called **quantum numbers**), Pauli determined that no two electrons in an atom could have all the same numbers. In addition, electrons' spin made them want to pair up in two's, almost like two magnets that happen to get stuck together N-S and S-N with their poles.

To make a *very* long story short, we now have a model of the electron space in an atom. It's like an organized set of residences, each able to hold two people. One way to think about it is as an *inverted pyramid*. That is, the bottom is small and the upper floors get larger. Each floor is labeled with a number, 1, 2, 3, etc. These are called **principal quantum numbers** or **principal energy levels** or **shells**. In each level there are **subshells** corresponding to other quantum numbers. These subshells can contain (in "double rooms") 2, 6, 10, and 14 electrons. They are labeled **s, p, d, and f** for historical reasons. To a large degree, nature fills these rooms in order from bottom to top, with some significant exceptions that we'll let your Chemistry teacher to explain. Here is a table-format summary for the first four shells:

Principal quantum #	s-space available	p-space available	d-space available	f-space available
1	2	n.a.	n.a.	n.a.
2	2	6	n.a.	n.a.
3	2	6	10	n.a.
4	2	6	10	14

Chemists have devised a notation for the electrons contained in atoms, including their ions. This is formally called the **electron configuration**, and the process of filling the shells from lowest energy to highest energy is called the **Aufbau principle** (German for “building up”). Here are the first 18 elements in the periodic table along with their electron configurations. It looks repetitive and boring, but if you pay attention, patterns become obvious

Name	Symbol	Configuration	Comment
hydrogen	H	$1s^1$	nonmetal
helium	He	$1s^2$	inert, noble gas
lithium	Li	$1s^2 2s^1$	very reactive, alkali metal
beryllium	Be	$1s^2 2s^2$	alkaline earth metal
boron	B	$1s^2 2s^2 2p^1$	metalloid
carbon	C	$1s^2 2s^2 2p^2$	nonmetal, semiconductor
nitrogen	N	$1s^2 2s^2 2p^3$	nonmetal, diatomic gas
oxygen	O	$1s^2 2s^2 2p^4$	nonmetal, diatomic gas
fluorine	F	$1s^2 2s^2 2p^5$	halogen, very reactive nonmetal
neon	Ne	$1s^2 2s^2 2p^6$	inert, noble gas
sodium	Na	$1s^2 2s^2 2p^6 3s^1$	very reactive, alkali metal
magnesium	Mg	$1s^2 2s^2 2p^6 3s^2$	alkaline earth metal
aluminum	Al	$1s^2 2s^2 2p^6 3s^2 3p^1$	metal
silicon	Si	$1s^2 2s^2 2p^6 3s^2 3p^2$	metalloid, semiconductor
phosphorus	P	$1s^2 2s^2 2p^6 3s^2 3p^3$	nonmetal
sulfur	S	$1s^2 2s^2 2p^6 3s^2 3p^4$	nonmetal
chlorine	Cl	$1s^2 2s^2 2p^6 3s^2 3p^5$	halogen, very reactive nonmetal
argon	Ar	$1s^2 2s^2 2p^6 3s^2 3p^6$	inert, noble gas

Look over the above table to convince yourself that there is some sort of pattern going on here. Check out elements that have the same final electron subshell notation, like  $2p^6$  and  $3p^6$ , etc. We'll soon see that where an element's outermost electrons reside determines that element's chemical and physical properties.

If you take a look at the noble gases (which tend to not react at all with other elements or themselves), their electrons have completely filled the s and p subshells of their highest shell. This seems to be a very stable situation - they have no tendency to lose or gain electrons. Notice also that the halogen gases are one electron *shy* of having a complete shell, and the alkali metals have one electron *more* than that of a full shell. Both of these families of elements are very reactive. Gaining or getting rid of an electron will give them the magic number of a filled shell. It is this kind of stability that nature seems to seek when atoms of elements begin to share their electrons with others.

The organization of the traditional **periodic table** is based solely on the shells and subshells. When the elements are arranged like this, you'll find similar properties among those elements in vertical columns. These are called **groups** or **families**. You already know several group names. An additional one, the group containing oxygen, sulfur, selenium, tellurium, and polonium is called the **chalcogens**. Most other families are not referred to by name. The horizontal rows are called **periods**. Notice in the periodic table that there are two periods which seem to not fit and are shown below the body of the table. These correspond to filling the 4f and 5f subshells. These special groups of metals are called the **Lanthanides** and **Actinides**, after the first element in each period. You'll note that the majority of elements are metals. If you draw a diagonal line on the periodic table from aluminum to polonium, elements above and to the right are generally nonmetals. Elements below and to the left are metals. A few metalloids fill out the table.

## 5. Bonding Between Atoms

The simplest bond to imagine with our model of the atom is the **ionic bond**. This is the type of bond you'll frequently find between metals and nonmetals. Let's use common table salt (sodium chloride) as an example. A sodium atom has one more electron than its nearest noble gas. If it lost one electron and became  $\text{Na}^+$ , it would be more stable. Chlorine is one electron shy of its nearest noble gas, so acquiring an electron and becoming  $\text{Cl}^-$  would fill its highest shell and make it more stable. That's exactly what happens. Sodium loses an electron to chlorine. They both become oppositely charged ions, and they then stick together in large arrays because of their opposite charges. We name the new compound *sodium chloride* and we symbolize it with the abbreviation *NaCl*. Notice that magnesium would like to lose *two* electrons to gain a noble gas number structure. It does exactly that, so in forming a compound with chlorine it ends up ionic bonding to *two* chlorine ions. We call its new molecule *magnesium chloride* and give it the formula  $\text{MgCl}_2$ . (It is standard practice to name the compounds with the metal name first.) In addition, we can use prefixes to note the number of atoms of an element in a molecule. Here is a chart of the prefixes:

Number of atoms	Prefix
1	mono
2	di
3	tri
4	tetra
5	penta
6	hexa
7	hepta
8	octa
9	nona
10	deca

Looking back to magnesium chloride, a better name would have been *magnesium dichloride*. This name would let us know right away that there are two chloride ions for every magnesium ion.

When bonding occurs between nonmetals, there is less of a difference between which element tends to lose or gain electrons. In these cases we tend to get more of a sharing of electrons. This type of bond is called **covalent bonding**. The oxygen you breathe exists in a diatomic form in nature. This means that there are two oxygen atoms per molecule. The way that happened can easily be seen from the periodic table. Notice that oxygen would like to gain two electrons to achieve a noble gas configuration. What happens is that two oxygen atoms each *share* two electrons. Now each feels it has the noble gas number and is stable. Same with hydrogen. If two hydrogen atoms each share *one* electron, each will now have the helium electron configuration - stable! In the case of identical atoms bonding, there will be an equal sharing of the electrons. However, bonding between different nonmetals usually has non-equal sharing. How strongly an element wants to retain these shared electrons was quantified by American chemist Linus Pauling. His **electronegativities** are relative values of the stinginess of an atom for electrons in bonds. The larger the number, the more that element wants the electrons. In the periodic table, electronegativity values tend to increase from left to right in periods and bottom to top in groups. The closer the electronegativities are to each other, the more even the sharing. Bonds made between elements with a larger difference in electronegativity tend to be **polar**. A **polar bond** is one in which the electrons spend more time with one atom than with the other. As a result, atoms that have more time with the electron seem more negative; the atoms with less electron time seem more positive. We'll come back to polar bonds later.

## 6. States of Matter

Now that we've reviewed molecules, we know they will have properties based on their mass, structure, and bonding. There is an interaction between molecules of the same compound based on mutual electric forces. Very polar molecules tend to stick together compared to completely non-polar ones. As a result, you will find compounds existing as solid, liquid, and gas. These three states of matter are differentiated as follows:

State	Shape	Volume
solid	definite	definite
liquid	indefinite	definite
gas	indefinite	indefinite

There is a fourth state of matter that occurs at very high temperatures called a **plasma**. (No relation to blood plasma). This is a gas-like state, but the atoms have lost some of their electrons, so the state is full of positive and negative particles and is very conductive. It may seem odd, but we won't concentrate on plasma at all, even though it is the most common state of matter in the universe. Stars are in the plasma state. And plasmas do exist on earth - the glowing gas in a fluorescent light is a plasma.

Most compounds can exist in any of the three normal states of matter, and temperature is the key to which state they will be in. You are already aware that water can exist as a solid (ice), liquid (water), or gas (vapor). Most compounds have two special temperatures which are called the **melting (freezing) point** and the **boiling (condensing) point**.

All materials above absolute zero have some molecular motion. When the motion is so small that molecules all stay in basically the same place, we say the substance is in the **solid** state. After adding more heat (kinetic energy) to the sample, the molecules may start sliding all around each other, though still remaining close together. This is our **liquid** state. Finally, if we give the molecules too much heat (kinetic energy), they will fly all over the place and they will have large spaces between molecules. This is a **gas**.

Compounds usually fall into one of two categories: **crystalline** or **amorphous** (also called **glasses**). Glasses do not have distinct temperatures at which they melt or boil. They just get soft when heated, sort of like taffy or tar. Crystalline solids will make the phase transition at very specific temperatures.

Back to water. Although the temperature can be manipulated a bit using pressure, solid water (ice) will melt at 0<sup>o</sup> C. Liquid water will boil at 100<sup>o</sup> C. Both processes

require addition of large amount of heat energy to get the molecules moving fast enough to separate. These heat quantities are called the **heat of fusion** (for melting) and **heat of vaporization** (for boiling/vaporizing). Each compound has a specific value for these two energies. If you are going from solid to liquid or liquid to gas, you must put *in* that amount of energy. This is called an **endothermic** process. But, if you go from gas to liquid or liquid to solid, the same amount of heat is given off! This is called an **exothermic** process. When we are wet and the water evaporates from our skin, we feel cooled because that liquid-to-gas process required energy which was taken away from our skin. When ice melts in a cooler, the same thing happens. But when water freezes or steam condenses, heat is given off. This is why the Chicago lake shore tends to be a bit warmer than the “boonies” during the winter, and why steam burns are much more dangerous than hot water burns.

In addition, it takes heat energy just to change the temperature of a solid, liquid, or gas. These are called the **specific heats** or **heat capacities** of materials. They are usually specified by how much energy is need to raise one gram of the substance by one degree Celsius. Water has an exceptionally high heat capacity, so it is an excellent heat storage material. Both the weather and climate of a region are influenced greatly by local large bodies of water.

## 7. The Gas Laws

Here we'll single out the gas phase for closer study. Gases have a very peculiar property that was first suggested by Amedeo Avogadro in 1811. Avogadro proposed that equal volumes of *any* gas at the same temperature and pressure would contain the same number of molecules, no matter their size or mass! That means if you have identical balloons filled with hydrogen, helium, carbon dioxide, or any other gas, you will have the same number of particles in each one. Another aspect of this is the **mole-volume relationship** of a gas. At standard temperature and pressure (0° C and 1 atm - STP for short) one mole of any gas will occupy 22.4 liters. This makes it easy to determine how much of a particular gas you have in a container.

What if the temperature changes? In 1787, Jacques Charles was able to show that the volume of a sample of gas (kept at the same pressure) is directly proportional to its *absolute* temperature. It makes sense that when you heat a sample of gas the molecules will move faster, have harder collisions with other gas molecules, and expand in volume. It's nice that it is a simple, direct proportion. All you must do is be sure you are working in kelvins and the following formula will find the new volume for you:

$$V_1/V_2 = T_1/T_2.$$

This is known as Charles Law. (Gay-Lussac's Law if you are French)

Pressure will also affect the volume of a gas, but this is an *inverse* relationship. Named for Charles Boyle, Boyle's Law can be written as:

$$P_1/P_2 = V_2/V_1$$



This is also very logical. If you squeeze a gas (which is mainly empty space) then its volume should get smaller. It is possible to put Avogadro, Charles, and Boyle altogether in one **combined gas law**. The result is

$$P V = n R T$$

where  $P$  = pressure,  $V$  = volume,  $n$  = number of moles of gas,  $R$  = Universal Gas Constant, and  $T$  = temperature. The value of the gas constant depends on which units you choose for pressure and volume. (Temperature must be in kelvins.) If volume is in liters and pressure in atmospheres,  $R = 0.082058$ . If volume is in cubic meters and pressure in pascals,  $R = 8.3145$ . Your calculator, then, can generate any of the unknowns (pressure, volume, number of moles, temperature) assuming you know all but one of the values.

Something that gases are good at doing is **diffusing** and **effusing**. Left on their own, a collection of different gases in a container will become evenly distributed so that if you took a sample from anywhere in the container, you'd get the same proportions of the different gases. This is because of the natural spreading out of a gas, called **diffusion**. If you close your eyes and someone walks into the room with a pizza, it won't be long before your nose tells you about the pizza. The aroma has diffused throughout the room.

The process of **effusion** is when a gas escapes from tiny holes in its container. Gas molecules are unbelievably small. Because they are constantly, randomly bouncing around, it is likely that a molecule will eventually try to go flying out of a hole in the container. The holes can be sub-microscopic, but as long as the molecules are smaller than the hole, effusion will take place. Helium gas atoms are exceptionally small and it is only a matter of time before a helium balloon will lose its contents. It takes a high-tech container to successfully keep helium (or hydrogen) gas confined.

## 8. Solutions

A **solution** is a homogeneous mixture of at least two compounds or elements. We give the name of **solvent** to the component that is most abundant, and **solute** to the component(s) that is (are) present in a smaller amounts. The solvents and solutes can be in any phase, solid, liquid, or gas. Examples of this are:

Solute	Solvent	Solution	Example
gas	gas	gas	air: O <sub>2</sub> , Ar, CO <sub>2</sub> in N <sub>2</sub>
gas	liquid	liquid	any soft drink: CO <sub>2</sub> in H <sub>2</sub> O
gas	solid	solid	special electrode: H <sub>2</sub> in Pd
liquid	liquid	liquid	vinegar: CH <sub>3</sub> COOH in H <sub>2</sub> O
solid	liquid	liquid	salt water: NaCl in H <sub>2</sub> O
solid	solid	solid	14-Karat gold: Ag in Au

There are a large number of different units used to specify how concentrated a solution is. Here are *some* of them with their operational definitions:

Name	Abbrev.	Definition/Calculation
molarity	M	moles solute/liters of solution
molality	m	moles solute/kilogram solvent
% by mass	%	mass solute/mass solution
% by volume	%	volume solute/volume solution
mole fraction or mole %	%	moles solute/moles solution
parts per million	ppm	mass solute/million solution
parts per billion	ppb	mass solute/billion solution
parts per trillion	ppt	mass solute/trillion solution
mass/volume	°brix *	grams sugar/100 mL solution
mass/volume	mg/dL **	mg of solute/dL of solution

(There are numerous mass/volume units in use.)

\*This unit is used in the food industry to indicate how sweet a liquid food product is. Grape juice at 20°brix would have 20 grams of sugar in each 100 mL of juice.

\*\*This unit is common in medicine. For example, a cholesterol reading of 165 means 165 mg of cholesterol in 1 dL (same as 100 mL) of blood.

Some other solution information: depending on the type of solute and solvent, the process of dissolving can be either endothermic or exothermic. With exothermic dissolving, care needs to be taken so that not too much heat is generated too quickly. In addition, **polar molecules** tend to dissolve better in **polar solvents**, and **non-polar molecules** dissolve better in **non-polar solvents**.

So many solutions are made using water that they have a special name: **aqueous**

## solutions.

In general, when dissolving solids in water, the *warmer* the water, the faster the dissolving process and more solute can be dissolved. The reverse is true for gases: the *colder* the water, the faster the dissolving process and the more gas you can dissolve.

Also, solutions tend to have higher boiling points (**boiling point elevation**) and lower freezing points (**freezing point depression**) than their pure solvents.

There is actually a type of mixture in between a true solution and a heterogeneous mixture. (Imagine salt water as a true solution and sand in water as the heterogeneous mixture.) It is possible to make the solid particles of some substances small enough so that they do not sink to the bottom of a liquid solvent, but they don't actually dissolve either. They are kept suspended by the energetic motions of the solvent molecules. These are called **colloids**. Like solutions, they can be made of different phases of matter. Some examples:

Dispersed phase	Medium phase	Name	Example
solid	liquid	sol	jelly, starch solution
liquid	liquid	emulsion	milk, mayonnaise
gas	liquid	foam	whipped cream, shaving cream
solid	gas	aerosol	fine dust in air
liquid	gas	aerosol	fog, hairspray
solid	solid	solid sol	rubies, black diamonds
liquid	solid	solid emulsion	pearls, opals, butter
gas	solid	solid foam	floating soap, pumice, foam insulation

## 9. Acids & Bases

Two of the most important types of compounds are called **acids** and **bases**. They play major roles in our everyday lives. They are important in many areas of chemistry.

**Acids** have a number of common properties as you might expect. They taste sour (orange juice, for instance), form conducting solutions in water, turn litmus paper red, react with most metals to form hydrogen gas, and react with common baking soda (calcium carbonate) to form carbon dioxide. They form hydrogen ions ( $H^+$ ) when dissolved in water.

Note: since a hydrogen ion would technically be just a loose proton, the ion

formed by an acid in water is often called the **hydronium ion** ( $\text{H}_3\text{O}^+$ ). This suggests that the loose hydrogen sort of adopts a water molecule as a transport vehicle while in solution.

**Bases** have the common properties of tasting bitter (milk is a base, though not so bitter...), form conducting solutions in water, turn litmus paper blue, and their solutions feel slippery. They form hydroxide ions ( $\text{OH}^-$ ) when dissolved in water.

When acids and bases react together they produce salts and water. If the acid has a single hydrogen available (a **monoprotic acid**) a simple salt and water is produced. If the acid has more than one hydrogen available (a **polyprotic acid**), the reaction will yield water and an **acid salt**. Acid salts have an extra hydrogen attached.

Acids and bases are often labeled as strong or weak based on how conductive their solutions become after dissolving. An acid or base labeled as strong is assumed to ionize 100% when dissolved in water. Weak acids and bases only partially ionize, making the hydrogen or hydroxide ion concentration considerably smaller than a strong acid or base.

A scale to express how acidic or basic an aqueous solution is has been developed. It is the pH scale. It is a scale that is based on the behavior of water to **autoionize**, that is, break up into hydrogen and hydroxide ions. Pure distilled water will break up into the two ions such that their molar concentrations are each  $1 \times 10^{-7}$ . The product of both concentrations, then, will be:

$$[\text{H}^+][\text{OH}^-] = [10^{-7}][10^{-7}] = 1 \times 10^{-14}$$

It turns out that in any aqueous solution, the product of the concentrations will be  $1 \times 10^{-14}$ .

The pH scale expresses the hydrogen ion concentration as a base 10 logarithm. The exact definition is:

$$\text{pH} = -\log_{10} [\text{H}^+]$$

Distilled water with a  $[\text{H}^+] = 10^{-7}$  would have a pH of:  $-\log_{10} [10^{-7}] = 7$ . This is considered exactly neutral water. *Any* acid added to distilled water would increase the  $[\text{H}^+]$  to a value greater than  $10^{-7}$  so the pH would be less than 7. The range of acid pH is from 0 to 7. If an aqueous solution is basic (more  $\text{OH}^-$  than  $\text{H}^+$ ), the pH would be from 7 to 14.

Summary:

<b>Solution status</b>	<b>[H<sup>+</sup>]</b>	<b>[OH<sup>-</sup>]</b>	<b>pH</b>
acidic	$> 10^{-7}$	$< 10^{-7}$	$< 7$
neutral	$10^{-7}$	$10^{-7}$	7
basic	$< 10^{-7}$	$> 10^{-7}$	$> 7$

Many chemical reactions that take place in our body must do so in a controlled pH situation. The pH of a solution can be stabilized (or **buffered**) in a very simple way. Recall that weak acids and bases do not ionize to a great degree. They *dissolve*, but they remain mostly in their full molecular form. A **buffer solution** is one that contains both a weak acid and a weak base. If a strong acid is added to the solution, the weak base can react with it. This results in some of the strong acid's hydrogen ions being converted into water. This will help raise the pH back to at nearly its original level. If a strong base is added to the solution, the weak acid will react with it in much the same way. It is important to note, though, that buffer solutions can usually only take care of limited amounts of strong acids or bases.

Aspirin is actually an acid. This acid can irritate the stomach lining of some people. The brand of aspirin *Bufferin* contains a buffering system to help reduce the acid effects for these people. Many shampoos contain buffering agents as well.

**Acid rain** is a serious environmental problem which is very slowly damaging forests, crops, and virtually anything containing limestone or metal that must stay out in the rain. A byproduct of our burning of coal and oil products, acid rain occurs over vast stretches of North America and Europe. Actually, with the earth's atmosphere in constant flux, there is no place on earth immune to this problem. Areas *downwind* of industrial areas are hardest hit. Acid rain is rain that has been acidified by one or more of at least four different reactions. Sulfur and nitrogen are two elements found in the emissions of internal combustion engines and power plants. Both eventually form oxides and then acids when combined with rain water. These acids are sulfuric, sulfurous, and nitric. In addition, carbon dioxide produced by burning these fuels also helps convert rain water to carbonic acid. Although the concentrations are quite low, the long term effects can be quite serious. Recall that one property of an acid is its ability to dissolve metals and limestone. These are two very common building materials and acid rain puts them at significant risk of damage.

## 10. Oxidation and Reduction

Another very common type of reaction involves an exchange of electrons between the reactants. In these reactions one of the reactants will give up one or more electrons. We say it has been **oxidized**. The other reactant will acquire these electrons and we say it has been **reduced**. As a whole the reaction is called an **oxidation-reduction reaction**, or **redox reaction** for short. One of these reactions closest to you is that in the batteries that you might use for an audio device, a cell phone, etc. Batteries (or **electrochemical cells** as they are also called) usually consist of two *different* metals. Metals can be ranked according to how readily they will lose or gain electrons. We saw this earlier when looking at individual chemical bonds. All you need to do to produce a simple battery is to obtain two different types of metal and put an ionic solution between them (the electrons need a way to move from one to the other). Perhaps the simplest is to drive a copper nail and a zinc-coated steel nail into a lemon. (The sour taste of lemon juice is citric acid.) While not strong enough to power your CD player, a small current of electrons *will* flow from the zinc nail to the copper nail if you

connect them with a piece of wire. (Remember circuits!) More efficient batteries can be made with zinc and carbon (the cheaper batteries you can buy). An alkaline chemistry produces a much better battery. If you use nickel and cadmium you can actually **recharge** (reverse the oxidation-reduction reaction) by applying a reverse voltage across the electrodes. A car battery usually has a lead - lead oxide chemistry to provide its strong power and easy recharging.

## 11. Reaction Rates and Equilibrium

How fast a chemical reaction takes place is very easy to understand if you remember the physics concerning temperature, collisions, and energy. For a reaction to take place, the two (or more) reactant atoms (or molecules) have to run into each other, form a temporary mess called an **activated complex**, and then separate into two (or more) products that are a different arrangement than before. That's chemistry in a nutshell!

It is important to note that there is a minimum amount of initial kinetic energy the reactants will need in order to successfully cause the reaction. It's not unlike striking a piñata. If you don't strike it hard enough, it won't break. In reactions this is called the **activation energy** . If the reactants aren't moving fast enough, the reaction won't take place. As a result, the temperature of the reactants plays a large role. Here is a summary of the factors that affect reaction rates:

Factor	Effect
activation energy	The lower the required activation energy, the faster the reaction will take place. This is because at a given temperature, more of the reactants will have sufficient energy
temperature	The higher the temperature, the faster the reactants are moving and the more kinetic energy they have. Refer right back to "activation energy"
reactant concentration	The more concentrated the reactants, the more likelihood there will be of a collision. Run across an empty beach and you'll not likely bump into anyone. Run across a crowded beach and
catalyst	The presence of a proper <u>catalyst</u> will lower the activation energy. Catalysts are elements or compounds that temporarily participate in the reaction, BUT are not used up. The <u>catalytic converter</u> that is part of a car's exhaust system uses platinum or
particle size	For reactions involving solids, having smaller pieces or particles will speed up the reaction. This is nothing more than increasing the surface area and therefore the concentration of reactants. Lighting a big log with a match is an impossibility. But, if you could somehow turn the log into a pile of fine

**Equilibrium** is a concept we've visited before in terms of physical stability. In chemistry, the concept of a **reversible reaction** is the idea that some reactions can be reversed so that what we initially call *reactants* become *products* and what we called *products* become *reactants*.

Some reactions are not reversible. Take burning hydrogen in oxygen. Combine them, ignite them with a spark. You get an explosion and the final products are water and a lot of thermal energy. The reverse reaction would be to take water and cool it. Will hydrogen and oxygen gas result? No way! This reaction tends to go in only the forward direction.

Many reactions, though, are indeed reversible. As a result, these reactions will stall at the point where the rate of production of the "products" exactly equals the production of the "reactants". After that point the reaction we thought of as *forward* no longer takes place. At least not in a way that we can detect. A physical example of this equilibrium is putting a small amount of water in a jar and then capping it. The water will initially evaporate, but eventually it will produce enough water vapor that the process of evaporation will equal the process of condensation. No more visible change will occur,

though both processes continue *at the same rate*.

How *far* a chemical reaction proceeds in the *forward* direction is given by its **equilibrium constant**,  $K_{eq}$  for short. We'll only look at two examples here, but to summarize, the equilibrium constant will be the product of the *product concentrations* divided by the product of the residual *reactant concentrations*. Let's burn gas **A** in gas **B**. If the reaction equation is:  $A_2 + B_2 \rightleftharpoons A_2B_2$  then the equilibrium constant would be:

$$K_{eq} = [A_2B_2] / [A_2][B_2].$$

If the number is large, the reaction must tend toward completion. Not many reactants are left over. If the number is small (less than 1) this reaction doesn't want to go "forward". If the reaction equation were different in this way:  $A_2 + B_2 \rightleftharpoons 2 AB$  then the equilibrium constant would be:

$$K_{eq} = [AB]^2 / [A_2][B_2].$$

Subtle difference, but very important. Check out examples in your chemistry book.

It is possible to disturb a chemical equilibrium just like it is to disturb a physical equilibrium. **Le Chatelier's Principle** let's us predict a qualitative outcome from such a disturbance. This principle couldn't be simpler. It states that if you **stress** a chemical system that is in equilibrium, the reaction will go which ever way (forward or backward) that will reduce that stress.

There are three main areas to remember:

Stress Imposed	Le Chatelier Response
increase concentration of reactant/product	The reaction will move to reduce that concentration increase. If you added a reactant, more product will be produced and vice versa
increase pressure	If gases are involved and you increase the pressure, which ever side of the equation has fewer particles will be favored and the reaction will move in that direction
increase temperature	For an exothermic reaction, products will be favored. For an endothermic reaction, products will be favored. Be sure you can explain this one to a friend. If you can, you've mastered Le Chatelier!

## 12. Organic Chemistry

**Organic chemistry** is a synonym for **carbon chemistry**. If there is one of the



elements in the periodic table that you should choose as your favorite (like a favorite sports star) it should be carbon. When you find it in the periodic table, you'll see it is in that questionable area between metals and nonmetals. It is a conductor, sort of. With most conductors, if you heat them up they become poorer conductors. Carbon is the reverse. Pure carbon can be as lowly as a lump of coal or as exciting as a sparkling diamond.

What is more important for us is that carbon is an element that is happiest making four bonds with other atoms. If carbon gains four electrons in bonding, it achieves the noble gas configuration of neon. Carbon is extremely flexible in its bonding. It can make four simple bonds and form a very symmetrical tetrahedral structure. It can form what are called **double** and **triple bonds** with multiple-shared electrons and achieve many other shapes. It can form long chains of carbon atoms. It can form six-sided, hexagonal rings that we can smell. Carbon-carbon bonds are extremely strong. Life as we know it is not possible without carbon and its unique chemistry.

Since we can only visit a few ideas here in this narrative, let's look at some basics. Let's first look at combining carbon with just carbon. There are two primary forms we find in nature. The first, with very strong bonding in one plane and weaker bonding perpendicular to the first, results in a fairly soft solid called graphite or coal. It breaks apart so easily that pencil leads take advantage of the layers of carbon slipping off onto rough paper surfaces!

A truly symmetric bonding of carbon with carbon results in a gemstone called diamond. The hardest natural substance we have, diamond is an illustration of how "less is more."

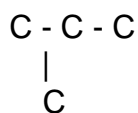
Now let's let carbon combine with other elements. Hydrogen is a good element to begin with. The number of compounds that can be made with just carbon and hydrogen is almost limitless. Called **hydrocarbons**, molecules with only hydrogen and carbon can form in many shapes and sizes. Allowing for *only* single bonds between carbons we have a family of molecules called **alkanes**. Here is a list of a few of the smallest alkanes:

Formula	Name
CH <sub>4</sub>	methane
C <sub>2</sub> H <sub>6</sub>	ethane
C <sub>3</sub> H <sub>8</sub>	propane
C <sub>4</sub> H <sub>10</sub>	butane
C <sub>5</sub> H <sub>12</sub>	pentane
C <sub>6</sub> H <sub>14</sub>	hexane
C <sub>7</sub> H <sub>16</sub>	heptane
C <sub>8</sub> H <sub>18</sub>	octane

In all of these, carbon makes only straight-line bonds with other carbon atoms, and all other bonding spots are filled with hydrogen. These are called **saturated hydrocarbons** because all bonding spots (non C-C) are filled (saturated) with hydrogen atoms.

A really neat thing about carbon is that at every spot available for a bond (that's four for every atom) you can attach anything that is happy with a single electron bond — ionic, covalent, it doesn't matter! As a result, there is incredible versatility. Isomers of hydrocarbons are plentiful and valuable. An **isomer** is a geometric variation of a molecule. The simplest to examine is butane. The formula for butane is C<sub>4</sub>H<sub>10</sub>. We can imagine the molecule to be a straight chain of four carbon atoms:

C - C - C - C or we can imagine the fourth carbon being attached to the middle carbon of a three-carbon chain:



In both cases we have butane with identical chemical formulas, but the chemical and physical properties of the two isomers will be different.

If we allow two adjacent carbon atoms to make a *double bond*, fewer hydrogens can attach, and we have very different compounds. These are called **alkenes**. C<sub>2</sub>H<sub>4</sub> would be the simplest. See if you can predict both the formula and shape of propene, butene, and pentene.

When a **triple bond** occurs between carbon atoms we call the resulting compound an **alkyne**. Predict formulas and shapes for ethyne, propyne and butyne.

Because of carbon's unique bonding geometry, it can also make a complete ring of six carbon atoms, the 6th atom bonding to the first. These are called **aromatic** hydrocarbons because many of them can be smelled. Benzene is the simplest. The ring has alternating double and single bonds, so the formula turns out to be  $C_6H_6$ .

Carbon doesn't bond to just hydrogen. If you remove one of the hydrogens in a hydrocarbon and replace it with an -OH, you automatically make an **alcohol**. Methane becomes methanol. Ethane becomes ethanol.

If you put an oxygen between two of the carbons in a chain you'll make an **ether**.

Add nitrogen and you'll have an **amine**. Add a double-bonded oxygen and an -OH group and you'll make a **carboxylic acid**. If you add all three of these you end up with a compound called an **amino acid** - building blocks of proteins. Glycine ( $C_2H_5NO_2$ ) is the simplest of these. These names should now be sounding a bit like biology, and in fact, that's where we are - **biochemistry**. This is organic chemistry as it applies to living things, and it is at the very core of our understanding of how living things operate. See more in the Genetics and Biochemistry sections of the GearUp biology study guide.

The chemistry of carbon is virtually boundless. Modern medicine depends on our knowledge of how organic molecules behave and interact. It is an exciting field of study that often produces very valuable results for us carbon-based life forms.

### 13. Nuclear Chemistry

We've looked at the nucleus a bit in the physics section of this study guide, so you should remember that we have a battle-of-sorts going on between the strong force (trying to hold the nucleus together) and the electric force (trying to blow the nucleus apart).

The early investigators in the late 19th and early 20th century included Henri Becquerel and Marie and Pierre Curie. They were responsible for the discoveries of the three types of radiation that come from nuclear change. Not knowing exactly what they were, the three rays were called "alpha, beta, and gamma" - Greek "A, B, and C". We've since learned that they are:

Name	Symbol	Actual Entity	Comment
alpha		He <sup>+2</sup> nucleus	Not very energetic. A sheet of paper will stop them.
beta		electron	Very energetic. Will penetrate aluminum foil 2-3 mm thick.
gamma		electromagnetic radiation	A form of e-m radiation, they can penetrate most materials easily.

Since these original discoveries, we've learned of two other ways a nucleus can decay or change:

1) **positron emission**. A **positron** is a positive electron, actually the antiparticle of the electron.

2) **electron capture**. **EC**, as it is called, is the absorption of an electron *in the nucleus* of an atom, not in its electron shells.

Here is a summary of the five types of nuclear decay and the effect each has on the nucleus.

Mode of decay	Radiation emitted	Atomic number change	Mass number change
alpha emission	He <sup>+2</sup>	-2	-4
beta emission	e <sup>-</sup>	+1	0
gamma emission*	rays	0	0
positron emission	e <sup>+</sup>	-1	0
electron capture	X-rays	-1	0

\*Note that in gamma emission it appears that nothing happens. Actually the nucleus loses energy in gamma emission and moves from a state called **metastable** to stable.

There are a number of naturally occurring radioactive nuclei. Hydrogen-3 (tritium) and carbon-14 are both produced in the upper atmosphere. They eventually become incorporated in organic molecules down here at ground level - even in you! All living things contain C-14 in trace amounts. Potassium-40 and thorium-232 are also important radioactive isotopes that occur naturally.

First we need to look at what are called **radioactive decay rates**. Each type of radioactive nucleus has a different tendency or rate of decaying. Some are fast; some are slow. One measure of how fast a nucleus tends to decay is the **half-life**. This is the length of time it takes for one half of the original nuclei to decay. Here is a list of some of the isotopes with practical uses.

Isotope	Half-life	Practical use
Carbon-11	20.4 min	PET scans
Carbon-14	5730 y	Dating archeological artifacts
Potassium-40	$1.25 \times 10^9$ y	Dating rocks
Cobalt-60	5.271 y	Treating cancer
Iodine-131	8.04 d	Tracer for thyroid studies
Uranium-238	$4.51 \times 10^9$ y	Dating rocks

\*y = years, d = days, min = minutes

The process of “dating” in the above table is a method for determining the age of a rock or an artifact. **Radiocarbon dating** is that process using carbon-14. The amount of C-14 in our atmosphere remains approximately constant. As a result living plants photosynthesize sugars having a small, constant fraction of C-14. Animals eat the plants - you included - and also contain that fraction of C-14. When a plant or animal dies, no new C-14 can be acquired. As time goes on, the fraction of C-14 in that plant or animal decreases. Knowing the half-life of C-14 (5730 y) the date when the plant or animal died can be determined. Because of the 5730 year half-life, C-14 dating does not work well for objects less than a few hundred years old (the amount of C-14 hasn't decreased enough) nor does it work well for objects older than 50,000 (there isn't enough C-14 left). Nonetheless, it is a very valuable tool for dating human artifacts associated with archeological sites.

In our physics section above we introduced the concepts of fission and fusion. Nuclear power reactors in the United States take advantage of the massive amount of energy contained in the nucleus of the uranium-235 atom. These atoms are allowed to fission under controlled conditions in large quantities of water. This water serves as a heat transfer material to eventually spin the turbines of the electric generators. Unfortunately, though the process is quite safe, a product of the reaction is plutonium-239 which is highly toxic and radioactive. Its half-life is 24,400 years. Disposal of this waste is a very controversial issue.

Fusing hydrogen nuclei to make helium is the long-term goal of nuclear scientists. This reaction is exactly what goes on in our sun and most stars. The “waste product” is a noble gas that doesn't react with anything! The problem we have is that to combine these hydrogen nuclei, a sustained temperature of 40 million kelvin is needed for the reaction. Not a problem in our sun. A massive problem here on earth. We are at the point where we've carried out the reaction in research generators for fractions of a second. Getting *sustained* nuclear fusion remains in the future. But - achieving that should end our energy woes.

Because of the high energy associated with nuclear radiation, it is something to be

avoided - for the most part. Too much radiation can be harmful. (The tiny, powerful rays can damage molecules in us.) However, having an xray image made at the doctor's or dentist's office is much less invasive than opening you up to take a look! Controlled use is valuable in this case. Also, using very high energy radiation to kill cancerous tumors is also worth the associated risks. It is a matter of balancing risk with benefit - something we should always be aware of.

Another use of radiation which is becoming more common is the **irradiation** of meats and vegetables to extend their shelf live. This process does *not* make the food product radioactive! What it does is kill harmful bacteria such as E. coli which is a principal cause of food poisoning. The only negative effects of irradiated food are that some starches may be broken down into sugars and some of pork's vitamin B<sub>1</sub> can be destroyed. Widespread acceptance of irradiated foods by people has been delayed by the lack of understanding of the process by the general public.

Although this is just a small sampling of the breadth and depth of physics and chemistry, hopefully it will be enough to spark your interest into digging a little deeper into science that affects you every moment of every day.