Novare Chemistry Supplement

An introductory resource for students using
Chemistry for Accelerated Students

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NOVARE
SCIENCE & MATH

Austin, Texas
2014

Published by
Novare Science & Math
P. O. Box 92934
Austin, Texas 78709-2934
novarescienceandmath.com

NOVARE
SCIENCE & MATH

Printed in the United States of America
ISBN: 978-0-9904397-0-7

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Chapter 1 Mass and Energy

Matter, energy, and intelligence (or "information") are the three fundamental components the created world is made of.[1] Mass and energy concepts are ubiquitous in chemistry, so a firm grasp on these concepts is essential.

Mass

The best way to understand mass is to begin with *matter* and its properties. The term *matter* refers to anything composed of atoms or parts of atoms. Your thoughts, your soul, and your favorite song are not matter. You can write down your thoughts in ink, which *is* matter, and your song can be recorded onto a CD, which is matter. But ideas and souls are not material and are not made of what we call matter.

In this section we will focus on just two properties that all matter possesses: all matter takes up space and all matter has inertia. Describing and comparing these two properties will help make clear what we mean by the term *mass*.

All matter takes up space. Even individual atoms and protons inside of atoms take up space. Now, how do we *quantify* how much space an object takes up? That is, how do we put a numerical measurement to it? The answer is, of course, by specifying its *volume*. Volume is the name of the variable we use to quantify how much space an object takes up. When we say that the volume of an object is 338 cubic centimeters, what we mean is that if we could hollow the object out and fill it up with little cubes, each with a volume of one cubic centimeter, it would take 338 of them to fill up the hollowed object.

All matter has inertia. The effect of this property is that objects resist being accelerated. The more inertia an object has, the more difficult it is to accelerate the object. For example, if the inertia of an object is small, as with say, a golf ball, the object will be easy to accelerate. Golf balls are easy to throw, and if you hit one with a golf club it will accelerate at a high rate to a very high speed. But if the amount of inertia an object has is large, as with say, a grand piano, the object will be difficult to accelerate. Just try throwing a grand piano or hitting one with a golf club and you will see that it doesn't accelerate at all. This is because the piano has a great deal more inertia than a golf ball.

As with the property of taking up space, we need to be able to quantify an object's inertia. The way we do this is with the variable we call *mass*. The mass of an object is a numerical measurement specifying the amount of inertia the object has. Since inertia is a property of matter, and since all matter is composed of atoms, it should be pretty obvious that the more atoms there are packed into an object, the more mass it will have. And since the different types of atoms themselves have different masses, an object made of more massive atoms will have more mass than an object made of an equal number of less massive atoms.

The main unit of measure we use to specify an object's mass is the *kilogram*. There are other units such as the gram and the microgram. The kilogram (kg) is one of the base units in the SI system of units (the metric system). On the earth, an object weighing 2.2 pounds (lb) has a mass of one kilogram. To give you an idea of what a kilogram mass feels like in your hand on

1 In this short chapter we will only discuss mass and energy. Those interested in a more detailed treatment of all three of these basics may wish to refer to my text, *Novare Physical Science*. See novarescienceandmath.com.

Figure 1-1. This battery has a mass of 1 kg.

the earth, the lantern battery pictured in Figure 1-1 weighs 2.2 lb, and thus has a mass of 1 kg.

We have established that the mass of an object is a measure of its inertia, which in turn depends on how many atoms it is composed of and how massive those atoms are. The implication of this is that an object's mass does not depend on where it is. A golf ball on the earth has the same mass as a golf ball at the bottom of the ocean, on the moon, or in outer space. Even where there is no gravity, the mass of the golf ball will be the same. This is what distinguishes the *mass* of an object from its *weight*.

Weight is caused by the force of gravity acting on an object composed of matter (which we often simply refer to as *a mass*). The weight of an object depends on where it is. An object—or mass—on the moon only weighs about 1/6 of its weight on earth, and in outer space, where there is no gravity, a mass has no weight at all. But the mass of an object does not depend on where it is. This is because an object's mass is based on the matter the object is made of. The lantern battery in the figure has a certain weight on the earth (2.2 lb). In outer space, it weighs nothing and will float right in front of you. But if you try to throw the battery, the force you feel on your hand will be the same on the earth or in space. That's because the force you feel depends on the object's mass.

Here is a summary using slightly different terminology. Inertia is a *quality* of all matter; mass is the *quantity* of a specific portion of matter. Inertia is a quality or property all matter possesses. Mass is a quantitative variable, and it specifies an amount of matter, a quantity of matter.

Energy

Defining energy is tricky. Dictionaries usually say, "the capacity to do mechanical work," which is not particularly helpful. So we are not going to try to define it accurately, we are just going to accept that energy exists in the universe, it was put there by God, and it exists in many different forms. It is fairly obvious that a bullet traveling at 2,000 ft/s has more energy than a bullet at rest. This is why the high speed bullet can kill but the bullet at rest cannot.

The Law of Conservation of Energy

The *law of conservation of energy* states that energy can be neither created nor destroyed, only changed in form. Energy can be in many different forms in different types of substances, such as in the molecules of gasoline, in the waves of a beam of light, in heat radiating through space, in moving objects, in compressed springs, or in objects raised vertically on earth. As different physical processes occur such as digesting food, throwing a ball, operating a machine, heating due to friction, or accelerating a race car, energy in one form is being converted into some other form. Energy might be in one form in one place, such as in the chemical potential energy in the molecules in the muscles of your arm, and be converted through a process like throwing a ball to become energy in another form in another place, like kinetic energy in the ball.

Strictly speaking, the law of conservation of energy is violated if nuclear processes are considered. This is because of the so-called mass-energy equivalence discovered by Albert

Einstein and forever enshrined in his famous equation, $E = mc^2$. In this equation E represents energy, m represents mass, and c represents the speed of light. As you can see, the constant of proportionality between mass and energy is the speed of light squared, a very large number. This explains why nuclear reactions, such as take place in stars and in nuclear weapons, release such a huge amount of energy. A tiny quantity of mass multiplied by c^2 results in a lot of energy. During nuclear reactions mass is actually converted into energy, creating energy when none was there before. For this reason we now say that the law of conservation of energy is only considered to hold across the board if the energy equivalence of mass is included.

Forms of Energy

There are many different forms of energy, some of which are described below. The first one, gravitational potential energy, is important to know about because we humans have a lot of direct experience with the way objects behave in gravitational fields. This makes gravitational potential energy a useful model or analogy for describing another form of energy we are less familiar with—electrical potential energy.

- *Gravitational Potential Energy*

  In a gravitational field such as we have on Earth, energy is required to lift an object vertically. If a crane hoists an object above the ground, the object will then possess *gravitational potential energy*. The term *potential* in the name of this form of energy indicates that the energy is stored and has the capability of converting into another form of energy when released. After having been raised up by the crane, if the object is released it will fall, and the gravitational potential energy is has will begin converting into kinetic energy, the energy associated with an object's motion. Immediately before hitting the ground, all of the gravitational potential energy the object had will have been converted into kinetic energy. To calculate gravitational potential energy, E_G, we use the equation

  $$E_G = mgh$$

  In this equation, m is the object's mass, g is the acceleration due to gravity on earth (9.80 m/s^2), and h is the object's height. Thus E_G is directly proportional to both an object's mass and its height.

- *Kinetic Energy*

  Kinetic energy is the energy an object possesses because it is in motion. Symbolized as E_K, kinetic energy is calculated as

  $$E_K = \tfrac{1}{2}mv^2$$

  The faster an object is moving, the more kinetic energy the object has. The kinetic energy of a moving object is directly proportional to its mass, and proportional to the square of the object's velocity.

- *Electromagnetic Radiation*

  Electromagnetic radiation is itself pure energy, and propagates in the form of electromagnetic waves traveling through space, or through media such as air or glass. This type of energy includes all forms of light (infrared, visible, ultraviolet, etc.), as well as radio waves, microwaves, x-rays, and gamma rays. Together, these make up the *electromagnetic spectrum*, a vast spectrum of electromagnetic radiation found in nature. The terms *light* and *electromagnetic radiation* are essentially synonyms, although in common speech we often use the term light to refer to light we can see with our eyes. But the other terms for electromagnetic radiation (microwaves, radio waves, x-rays, etc.) all refer to this same form of energy. The only difference is in the *wavelength* of the electromagnetic waves. Graphically, the wavelength of a wave may be represented as shown in Figure 1-2. The velocity of a wave relates to the wavelength and frequency of the wave as follows:

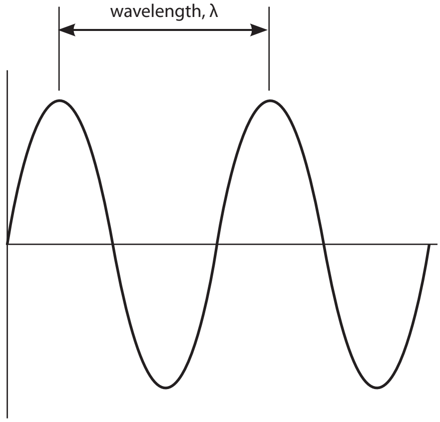

Figure 1-2. The parts of a wave. Two complete cycles of the wave are shown in the figure.

$$v = \lambda f$$

In this equation, v is the velocity of the wave, which for electromagnetic radiation is the speed of light measured, in units of meters per second (m/s). The other variables are λ ("lambda," the Greek letter l), the wavelength of the wave measured in meters (m), and f, the frequency of the wave measured in units called hertz (Hz). The *frequency* of a wave is the number of wave cycles the wave completes in one second. The unit "hertz" simply means cycles per second. So if a wave completes 5,000 cycles per second, its frequency is 5,000 Hz or 5 kHz.

As you can see from this equation, the velocity of a wave varies directly with its wavelength and directly with its frequency. But physically, it is better to think of the wavelength as depending on the other two variables in this equation. This is because the wave velocity actually depends on the medium in which the wave is propagating. Also, the frequency depends on the source of the wave; whatever is causing the wave is oscillating at a certain rate, and this rate determines the frequency of the wave being produced. So since the wave velocity is determined by the medium, and the frequency is determined by the source of the wave, this means the wavelength is the variable that really depends on the other two. So solving the wave equation for the wavelength as the dependent variable, we have

$$\lambda = \frac{v}{f}$$

From this form of the equation we see that the wavelength and frequency of a wave are inversely proportional. Higher frequencies have shorter wavelengths.

Here is an example calculation using this equation.

Radio station KUT FM in Austin broadcasts a carrier signal at 90.5 MHz. Determine the wavelength of this wave.

All radio waves (FM, AM, short wave, etc.) are part of the electromagnetic spectrum and propagate at the speed of light. We begin by writing the given information. Then we perform the needed unit conversions so that all quantities are in MKS (meter-kilogram-second) units.

$$f = 90.5\ \text{MHz} \cdot \frac{1 \times 10^6\ \text{Hz}}{1\ \text{MHz}} = 9.05 \times 10^7\ \text{Hz}$$

$$v = 2.998 \times 10^8\ \frac{\text{m}}{\text{s}}$$

Next, we write the equation, insert the values, and compute the result.

$$\lambda = \frac{v}{f} = \frac{2.998 \times 10^8\ \frac{\text{m}}{\text{s}}}{9.05 \times 10^7\ \text{Hz}} = 3.31\ \text{m}$$

The given frequency has three significant digits, so the result does as well.

- *Electrical Potential Energy*

  The best way to understand electrical potential energy is by analogy with gravitational potential energy. Objects with mass exert a gravitational attraction on one another. We describe this phenomenon by saying that a mass generates a gravitational field around itself, and any other object entering the field will feel the attraction of the gravitational force. In the same way, objects with electrical charge exert an electrical attraction or repulsion on each other. We describe this effect by saying that a charged particle generates an electrical field around itself, and any other charged particle entering the field will feel the attraction or repulsion of the electrical force.

  As explained in the Introduction to the main text, the concept of the electrical forces between charged particles (protons and electrons) is one of the central organizing ideas in chemistry. Interestingly, the mathematical descriptions of electrical and gravitational fields are structurally identical, and this is why gravitational fields and gravitational potential energy are so useful in helping us to understand electrical fields and electrical potential energy. In fact, for our purposes there are only two main differences between the gravitational and electrical forces. First, the electrical force is 10^{36} times as strong as the gravitational force! To give you some idea of how huge this number is, consider this. If you had a stack of 10^{36} sheets of copy paper, the height of this stack would be a distance that is about 100 billion (100,000,000,000) times the diameter of the entire Milky Way galaxy, which itself is 100,000 light years across. The bottom line is that in chemistry, gravity basically doesn't matter at all because the electrical forces between charged particles are so colossal by comparison. Second, gravitational forces are always attractive but electrical forces can be repulsive or attractive, depending on whether the signs of the charges involved are the same or opposite. Thus, gravitational potential energy appears when objects attracted to one another are pulled apart. The potential energy between oppositely charged particles works the same way. But particles possessing like charge (both positive or both negative) repel each other, so potential energy appears when two such charges are pushed together.

Natural processes like chemical reactions tend to go in a direction that minimizes the potential energy. This is illustrated in Figure 1-3. Left to themselves, objects attracted by the gravitational force will come together (a), which is why objects fall to the ground when released. By falling together, the potential energy between them is minimized. Objects experiencing electrical forces minimize the potential energy between them either by coming together (b) or by pushing apart (c).

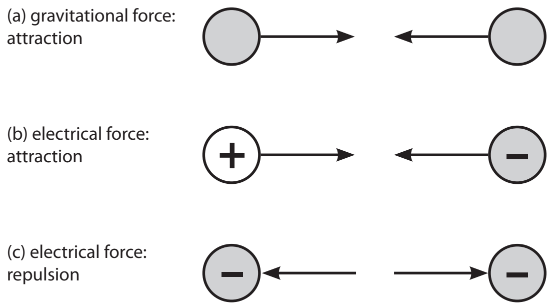

Figure 1-3. Comparison of gravitational and electrical forces.

- *Electrical Energy*

Since around 1800, we have known how to transport energy in electrical form in wires. These days just about everything is (or can be) powered electrically. For our study of chemistry, electrical energy will only play a role toward the end of the course when we study oxidation-reduction (redox) chemistry. In the redox chapter we will address the subject of electrochemistry, and at that point energy flowing in electrical wires will come into play.

Electricity is the flow of electrons in wires. Electrons are negatively charged, and in an electrical field electrons will flow toward the positive terminal of a battery or other power source. In a more general sense, any flow of charged particles constitutes an electric current. In copper wires, the moving charges are electrons. In an aqueous solution (a solution in water), the charges are often ions—atoms or clusters of atoms with a net charge.

- *Thermal Energy and Internal Energy*

Thermal energy is a general term that refers to the energy a hot object or substance possesses because it has been heated. The *internal energy* of a substance is the total of all of the kinetic energies possessed by the atoms or molecules of the substance. Atoms or molecules are constantly in motion, vibrating or translating, or both. Atoms in solids cannot fly around, so they vibrate in place, but atoms in fluids are free to translate, or move around. Either way, since atoms are always moving each one possesses an average kinetic energy, $E_K = \frac{1}{2}mv^2$. If you add up the kinetic energy of every particle in a certain substance, that total is its internal energy. This term is much more precise than the term thermal energy, and can actually be computed.

The internal energy of a substance correlates directly to its temperature. The higher the temperature, the higher the internal energy in the substance, which in turn implies faster moving particles. The concepts of internal energy and temperature relate immediately to the concept of absolute zero. Absolute zero is the zero temperature on the Kelvin temperature scale. The temperature of a substance varies directly with its internal energy. A temperature of 0 kelvins (absolute zero) means no internal energy at all, or in other words, atoms standing still! Atoms can't move any slower than standing still, and thus, there is no temperature lower than absolute zero. As far as we know, there is no place in the universe where the temperature is absolute zero, although physicists in low-temperature research labs have succeeded in achieving temperatures of only a few millionths of a degree above absolute zero.

- *Work*

  In physics, the term *work* denotes a mechanical process by which a specific amount of energy is transferred from one object to another. Objects do not possess work energy, as they do other with forms of energy. Instead, one object "does work" on another by applying a force to it and moving it a certain distance. When one object does work on another, energy is transferred from the first object to the second.

  The way an object acquires kinetic energy or gravitational potential energy is that another object or person or machine does work on it. Work is the way mechanical energy is transferred from one machine or object to another. Work is defined as the energy it takes to push an object with a certain (constant) force over a certain distance. Work is calculated as

  $$W = Fd$$

  where F is the force on an object, measured in newtons (N), d is the distance it moves (m), and W is the work done on the object, measured in joules (J), the standard unit of measure in the SI system for quantities of energy.

  If you push a person on a bicycle over a certain distance, you deliver energy to the person on the bicycle equal to the pushing force times the distance pushed. Assuming there is no friction, the work energy that comes from the pusher (you) is now in the kinetic energy of the person on the bicycle. (If there is friction, then some of the energy will convert into heat.) As another example, if you raise an object up above the ground you are doing work on the object. The force required to lift it is its weight, so the energy required to lift an object is the object's weight times the height it is lifted.

- *Heat*

  In physics, the term *heat* denotes energy in transit, flowing by various means from a hot substance to a cooler substance when a difference in temperature is present. Notice that heat is like work—both terms describe processes by which specific amounts of energy are transferred from one place to another. As with work, objects do not possess heat. After being heated, we would speak of an object's thermal energy or its internal energy.

  Heat is always absorbed or released in chemical reactions. Consider holding a beaker in your hand while a chemical reaction takes place inside the beaker. If the beaker feels hot, it is because the reaction is releasing energy in the form of heat, and you can feel this heat. Heat flowing into the water from the reaction in the beaker increases the internal energy in the water, and thus its temperature. Any process that releases heat like this is said to be *exothermic*. If the beaker feels cold, it is because the reaction is absorbing energy in the form of heat, and heat is flowing from the water in the beaker into the compounds being formed by the reaction. Since heat is flowing out of the H_2O and into the compounds formed by the reaction, the internal energy of the water decreases, along with its temperature.

  There are three different mechanisms by which heat can flow. The first is *conduction*, which occurs primarily in solids. In conduction, absorption of heat by the atoms in one part of the solid causes the atoms to vibrate more vigorously. This means higher kinetic energy and higher temperature. These vigorous vibrations then spread atom by atom throughout the solid. In metals, the spread of heat is also facilitated by the free electrons that collide and spread heat through the metal.

The second heat transfer mechanism is *convection*. Convection occurs in liquids and gases where molecules are free to fly around, collide, and mix and mingle. This process allows the thermal energy in a hot fluid (liquid or gas) to spread into a region of cooler fluid, and the kinetic energy is spread molecule to molecule through molecular collisions.

The third heat transfer mechanism is *electromagnetic radiation*. The region of the electromagnetic spectrum primarily associated with heat is the infrared region. When you feel warm standing in the sun or in front of a fire it is because the energy of infrared electromagnetic radiation is being absorbed by your skin. A fire is an exothermic chemical reaction, and fires release a lot of infrared electromagnetic radiation.

Questions

1. Distinguish between matter and mass.
2. Explain the difference between mass and weight.
3. In reference to waves, what does the term *frequency* refer to?
4. What makes work and heat different from the other forms of energy described in this chapter?
5. In what ways are electrical potential energy and gravitational potential energy similar?
6. What are two significant ways that the forces of electrical attraction and gravitational attraction are different?
7. How does the internal energy of a substance relate to the temperature of that substance?
8. When an object falls from a given height, it accelerates downward and its kinetic energy increases. According to the law of conservation of energy, energy is not created in this scenario; it comes from somewhere else. Explain where the increasing kinetic energy of a falling object is coming from. Then speculate on where the energy might have been before that.
9. Distinguish between thermal energy and internal energy.
10. Determine the wavelength of a radio signal broadcasting at 1,310 kHz. *(Ans: 229 m)*
11. In air, sound travels at approximately 342 m/s. The wavelength of the lowest note on a standard electric bass guitar is 8.30 m. Determine the frequency of the sound wave. *(Ans: 41.2 Hz)*
12. Determine the frequency of the light waves in a laser beam if the laser has a wavelength of 532 nm. State your result in GHz. *(Ans: 6.45×10^7 GHz)*
13. Determine the energy (work) required for a force of 2.11×10^{-3} N to move an object 9.50 m. *(Ans: 0.0200 J)*
14. Imagine that 175.0 mJ of energy are required to move an object 1,600.0 μm. What force was required to move the object? *(Ans: 109,400 N)*

Chapter 2 Atoms and Atomic Theory

A Review of Atomic Facts

All matter is made of atoms, the smallest basic units matter is composed of. An atom of a given element is the smallest unit of matter that possesses all of the properties of that element.

Atoms are almost entirely empty space. Each atom has an incredibly tiny nucleus in the center containing all of the atom's protons and neutrons. Since the protons and the neutrons are in the nucleus, they are collectively called *nucleons*. The masses of protons and neutrons are very nearly the same, although the neutron mass is slightly greater. Each proton and neutron has nearly 2,000 times the mass of an electron, so the nucleus of an atom contains practically all of the atom's mass. Outside the nucleus is a weird sort of cloud surrounding the nucleus containing the atom's electrons.

We will save the details about electrons for the main text, but here is a brief preview. The electron cloud consists of different *orbitals* where the electrons are contained. Electrons are sorted into the atomic orbitals according to the amount of energy they each have. For an electron to be in a specific orbital means the electron has a certain amount of energy—no more, no less.

We can say that atoms are almost entirely empty space because the nucleus is incredibly small compared to the overall size of the atom with its electron cloud. It's quite easy for us to pass over that remark without pausing to consider what it means. To help visualize the meaning, consider the athletic stadium picture in Figure 2-1. Using this stadium as an enlarged atomic model, the electrons in their orbitals would be zipping around in the region where the seating sections are in the stadium. Each electron in this vast space is far smaller than the period at the end of this sentence. The atomic nucleus containing the protons and neutrons is located at the center of the playing field and is the size of a pinhead. The rest of the space in the atom is completely empty. Nothing is there, not even air, since air, of course, is also made of atoms.

Returning to our discussion of atomic facts, one of the fundamental physical properties of the subatomic particles is *electric charge*. Neutrons have no electric charge. They are electrically neutral, hence their name. Protons and electrons each contain exactly the same amount of charge, but the charge on protons is positive and the charge on electrons is negative. If an atom or molecule has no net electric charge, it contains equal numbers of protons and electrons.

Figure 2-1. The head of a pin at center field in a stadium is analogous to the nucleus in the center of an atom.

Atoms are significantly smaller than the wavelengths of light (about 5,000 times smaller), which means light does not reflect off atoms and there is no way to see them. The same is true of *molecules*. Molecules are clusters of atoms chemically bonded together. When atoms of different elements are bonded together in a molecule they form a compound, which we will discuss in the next chapter of this booklet. But sometimes atoms of the same element bond together in molecules, as illustrated in Figure 2-2. Oxygen, chlorine, nitrogen, and hydrogen are common *diatomic gases* that form molecules consisting of a pair of atoms chemically bound together.

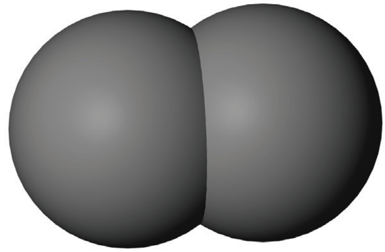

Figure 2-2. Space-filling model of a diatomic molecule.

Ions

An atom that is electrically neutral possesses an equal number of protons and electrons. This is the way we normally think of isolated atoms. But in many chemical process, atoms gain or lose electrons and thus have a net charge equal to the number of electrons gained or lost. If the atom gains electrons, its net charge is negative. If the atom loses electrons, it then has more protons than electrons and its net charge is positive. Any atom that has a net charge is referred to as an *ion*. Ions come up in nearly every chapter of the main text.

The process of gaining or losing electrons is called *ionization*. For reasons that will be explained in the main text, the ways atoms of some elements will ionize are very predictable. Have a look at the Periodic Table of the Elements you will find inside the back cover of your text (*Chemistry for Accelerated Students*). The elements you see listed in the first column—which is called Group 1—all ionize by losing one electron. All the elements listed in Group 2 ionize by losing two electrons. On the right end of the periodic table, elements in Group 18 don't ionize at all.[1] These elements are called the noble gases. Elements in Group 17 ionize by gaining one electron, and elements in Group 16 ionize by gaining two electrons. Similarly, most of the elements in Group 3 ionize to +3, and the first two elements in Group 15 ionize to −3.

If an atom of an element ionizes by gaining an electron, as chlorine does (Group 17), the atom is then an ion with a charge of −1. We denote this by placing the charge as a superscript on the element's chemical symbol, as in Cl^-. If an ion such as calcium has a charge of +2, (Group 2), then we write Ca^{2+}. Notice that if the ionic charge is +1 or −1, the 1 is not written in the superscript. Notice also that in the superscript on an ion we conventionally write the sign of the charge after the value of the charge.

Ions can also form where several atoms are bonded together in a molecule and as a group they have a net charge. These ions are called *polyatomic* ("many-atomed") *ions*. Common examples are hydroxide, OH^-, carbonate, CO_3^{2-}, and sulfate, SO_4^{2-}. Polyatomic ions are discussed in detail in the main text, so we will leave the rest of this topic for treatment there.

The History of Atomic Models

The story of atomic theory starts back with the ancient Greeks. As we look at how the contemporary model of the atom developed, we will hit on some of the great milestones in the history of chemistry and physics along the way.

1 Except under extreme conditions, such as those inside stars, plasmas, or specially contrived in laboratories.