Making Connections

6. Select one of the elements listed in **Table 4**.
   (a) Where does it come from, how is it extracted, and what is it used for?
   (b) Does it pose any health or environmental hazards? How should it be handled?
   (c) Do the advantages of having this element available outweigh the drawbacks? To help you decide, separate your findings into two categories: advantages and drawbacks. Write a paragraph summarizing your findings and explaining your position.

   Follow the links for Nelson Chemistry 11, 1.1.

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1.2 Developing a Model of the Atom

empirical knowledge: knowledge coming directly from observations

theoretical knowledge: knowledge based on ideas created to explain observations

model: a mental or physical representation of a theoretical concept

analogy: a comparison of a situation, object, or event with more familiar ideas, objects, or events

theory: a comprehensive set of ideas that explains a law or a large number of related observations

In all aspects of our lives, we can achieve understanding through observations (experience). The same is true in science: Understanding comes from observing the natural world and trying to make sense of those observations. All scientific knowledge can be classified as either empirical (observable) or theoretical (non-observable). Generally, **empirical knowledge** comes first, and can be as simple as a description or as complex as a powerful scientific law. For example, the physical and chemical properties of some elements were known empirically for thousands of years before we had a theory to explain these properties. This is a common occurrence: Empirical knowledge is usually well developed before any explanation is generally accepted within the scientific community. Although scientific laws are important statements summarizing considerable empirical knowledge, they contain no explanation. For an explanation—an answer to the question "Why?"—a theory is required.

So far in this chapter, you have encountered only empirical knowledge of elements, based on what has been observed. But why do the properties of elements vary across the periodic table? Why are groups of elements similar in their physical and chemical properties? Can we explain the chemical formulas of compounds formed from elements? An answer to these and other questions about elements requires a theory about what makes up elements.

Curiosity leads scientists to try to explain nature in terms of what cannot be observed. This step—formulating ideas to explain observations—is the essence of **theoretical knowledge** in science. Albert Einstein referred to theoretical knowledge as "free creations of the human mind."

It is more challenging to communicate theoretical knowledge than empirical knowledge because ideas are, by definition, abstract and cannot be seen. Theoretical knowledge can be communicated in a variety of ways such as words, symbols, **models**, and **analogies**. The difference between an analogy and a model is not always obvious. Models are representations (**Figure 1**). Analogies are comparisons. For example, some properties of a liquid can be explained using the analogy of a crowd of people in a confined space.

Figure 1
A physical model to represent the motion of particles described by the kinetic molecular theory of gases could be a vibrating box containing marbles. In what ways is this model useful in describing air in a sealed container? In what ways is it deficient?

Theories are dynamic; they continually undergo refinement and change. To be acceptable to the scientific community, theories must

- *describe* observations in terms of non-observable ideas;
- *explain* observations by means of ideas or models;
- successfully *predict* results of future experiments; and
- be as *simple* as possible in concept and application.

Activity 1.2.1

Developing a Model of a Black Box

Have you ever tried to figure out the contents of a package you weren't allowed to open? Such an object is often referred to as a "black box." The atom is a good example of a black box. Although, by definition, we can never open a black box, we can perform operations on the box that will help us to learn more about what goes on inside it. In this activity, you will be provided with a sealed container which, together with its contents, represents a black box. You are expected to investigate your black box and provide a detailed description of it. Your description should help you to develop a model of your black box.

Materials

black box (sealed box containing an object)

Procedure

1. Obtain a "black box."
2. Manipulate the box in a variety of different ways, without opening or damaging the box. Record the results as you proceed.
3. Write a preliminary description of the object inside the box.
4. Test your model and try to improve it by doing further manipulations.

Analysis

(a) Write a detailed description of the object in the box.
(b) Which manipulations were most useful in developing your model?
(c) Can you definitely say what your object is *not* like? Can you definitely say what it *is* like?
(d) What would you require to further develop your model? Give your reasoning.

Synthesis

(e) How is investigating the contents of a black box different from investigating the nature of the atom?
(f) Everyday life provides us with many examples of black boxes—things or relationships that we cannot break open to look inside. What is a black box for some may not be for others. Give three examples of black boxes that you have encountered.

Early Greek Theories of Matter

The Greek philosopher Democritus (460?–370? B.C.) first proposed an atomic theory of matter in the 5th century B.C. According to Democritus, all matter could be divided into smaller and smaller pieces until a single indivisible particle was reached. He called this particle an **atom**. He believed that different atoms are of different sizes, have regular geometric shapes, and are in constant motion. He also believed that there is empty space between atoms.

Aristotle (384–322 B.C.) severely criticized Democritus's theory, arguing that the idea of atoms in continuous motion in a void is illogical. The concept of a void was very controversial at the time, and of course there was no evidence that a completely empty space could exist. Instead, Aristotle supported the four-

DID YOU KNOW ?

Theoretical Knowledge

There is a range of types of theoretical knowledge, just as there is for empirical knowledge.

- Theoretical descriptions are specific statements based on theories or models. For example, "a molecule of water is composed of two hydrogen atoms and one oxygen atom."
- Theoretical hypotheses are ideas that are untested or tentative. For example, "protons are composed of quarks that may themselves be composed of smaller particles."
- Theoretical definitions are general statements that characterize the nature of a substance or a process. For example, a solid is theoretically defined as "a closely packed arrangement of particles, each vibrating about a fixed location in the substance."
- Theories are comprehensive sets of ideas that explain a large number of observations. For example, the concept that matter is composed of atoms is part of atomic theory; atomic theory explains many of the properties of materials.

atom: the smallest particle of an element that has all the properties of that element (theoretical definition)

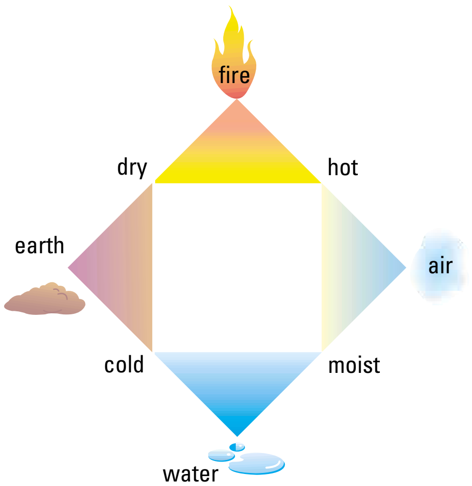

Figure 2
In Aristotle's model of matter, each basic substance, or element, possesses two of four essential qualities. For example, earth is dry and cold; fire is dry and hot. This model was based on logical thinking, but not on experimentation.

alchemy: a medieval chemical philosophy or practice, the principal goals of which were to transmute elements (e.g., lead to gold), to cure all illnesses, and to manufacture an essence that would allow long life

quantitative: involving measurements related to number or quantity

law of conservation of mass: the law stating that during a chemical reaction matter is neither created nor destroyed

law of constant composition: the law stating that compounds always have the same percentage composition by mass

Figure 3
Alchemists sought a method for transforming other metals into gold. Although they failed in their quest, they discovered new elements and compounds and developed many experimental procedures that are still used today.

element theory of matter. Proposed by Empedocles a century earlier (c. 495–435 B.C.), the theory was based on the idea that all matter is made up of four basic substances: earth, water, air, and fire. Aristotle and his followers believed that each of these basic substances had different combinations of four specific qualities: dry, moist, cold, and hot (**Figure 2**). Aristotle's theory of the structure of matter was the prevailing model for almost 2000 years, including the period of **alchemy** in the Middle Ages (**Figure 3**). The demise of Aristotle's model followed the scientific revolution in physics and the new emphasis, in the 18th century, on **quantitative** studies. Careful observations showed that too many of the explanations and predictions using Aristotle's theory were false. Scientists and philosophers needed a new theory with a different model of matter. This led to the revival of the atom concept.

Dalton's Atomic Theory

John Dalton (1766–1844), an English scientist and schoolteacher, proposed explanations for many of the known laws describing the behaviour of matter. Dalton expanded upon the atomic theory proposed by Democritus. This expanded theory was first introduced in 1803, at last replacing Aristotle's model of matter. Dalton's theory consisted of the following statements.

- All matter is composed of tiny, indivisible particles called atoms.
- All atoms of an element have identical properties.
- Atoms of different elements have different properties.
- Atoms of two or more elements can combine in constant ratios to form new substances.
- In chemical reactions, atoms join together or separate from each other but are not destroyed.

According to Dalton's theory, atoms are neither created nor destroyed in a chemical reaction. Since atoms are indivisible, and are only rearranged during chemical reactions, you must end up with the same number and kinds of atoms after a chemical reaction as you had at the beginning. Therefore, there will be no change in mass during chemical reactions. This explains the **law of conservation of mass**. Dalton's theory also suggested that atoms combine to form molecules in a fixed ratio in a given chemical reaction. Since the atoms of an element have identical properties, such as mass, and combine in constant ratios, every compound must have a fixed, definite composition. This explains the **law of constant composition**.

This introduction of atomic theory to the scientific world was followed by a period of intense investigation into the nature of matter. As a result of this investigation, Dalton's statements suggesting that the atom is indivisible and that all atoms of a given element have identical properties are no longer considered valid. Nonetheless, Dalton's theory proved very successful in explaining the laws of conservation of mass and constant composition.

Development of Atomic Theory from 1803 to 1920

By the late 1800s, several experimental results conflicted with Dalton's atomic theory. Technological advances made possible the construction of evacuated glass tubes fitted with an electrode at either end. The apparatus eventually became known as a cathode ray tube, named for the electrical discharge of particles assumed to be travelling from the negative electrode (or cathode) to the positive electrode (or anode). Several scientists used this apparatus in attempts to determine the composition of the atom. In one such experiment, conducted in 1897, J. J. Thomson (1856–1940) used a modified cathode ray tube to measure the mass of the particle and its electric charge. From his analysis of the results, which included calculating the mass-to-charge ratio for the mysterious particles, Thomson made a bold suggestion. He proposed that the cathode rays were subatomic particles: a subdivision of the matter from which all elements are built. Thomson had hypothesized the existence of **electrons**.

With this new idea, Thomson developed a new model of the atom: He suggested that negatively charged electrons are distributed inside the atom, which is a positively charged sphere consisting mostly of empty space (**Figure 4(a)**). In 1904, Japanese scientist Hantaro Nagaoka (1865–1950) represented the atom as a large, positively charged sphere surrounded by a ring of negative electrons (**Figure 4(b)**). Until 1911, there was no evidence to contradict either of these models.

In 1911, an experiment was performed that tested the existing atomic models. The experiment was designed by Ernest Rutherford (1871–1937) and involved shooting alpha particles (small, positively charged particles produced by radioactive decay) through very thin pieces of gold foil. Based on J. J. Thomson's model of the atom and his belief that the atom was composed mostly of empty space, Rutherford predicted that all the alpha particles would travel through the foil largely unaffected by the atoms of gold. Although most of the alpha particles did pass easily through the foil, a small percentage of particles was deflected at large angles (**Figure 5**). Based on this evidence, Rutherford hypothesized that an atom must contain a positively charged core, the **nucleus**, which is surrounded by a predominantly empty space containing negative electrons (**Figure 6**, page 26). By finding the percentage of deflected alpha particles and the deflection angles, Rutherford determined that only a very small portion of the total volume of an atom could be attributed to the nucleus.

Despite its tiny volume, most of the mass of an atom is believed to be concentrated in the nucleus. Consequently, the nucleus is often described as a dense central core that is massive compared to the electrons. In 1914, Rutherford coined the word **proton** for the smallest unit of positive charge in the nucleus.

In 1932, James Chadwick's experiments led him to modify Rutherford's atomic model. Chadwick (1891–1974) demonstrated that atomic nuclei must contain heavy neutral particles as well as positive particles. These neutral subatomic particles are called **neutrons**. Most chemical and physical properties of elements can be explained in terms of these three subatomic particles—electrons, protons, and neutrons (**Table 1**, page 26). An atom is composed of a nucleus, containing protons and neutrons, and a number of electrons equal to the number of protons; an atom is electrically neutral.

electron: a negatively charged subatomic particle

nucleus: the small, positively charged centre of the atom

proton: a positively charged subatomic particle in the nucleus of an atom

neutron: an uncharged subatomic particle in the nucleus of an atom

Note that these are all theoretical definitions.

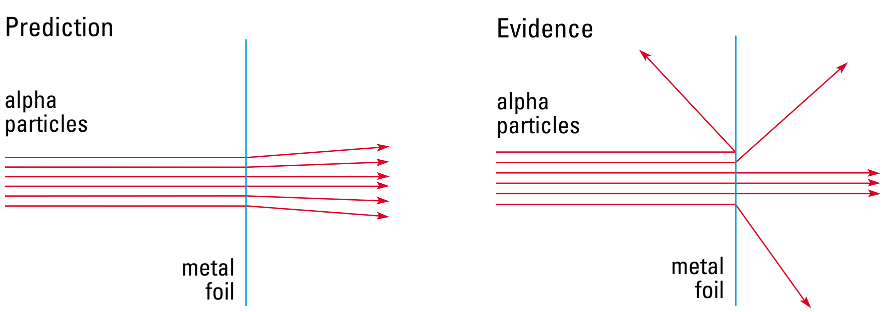

Figure 5
Rutherford's experimental observations were dramatically different from what he had expected.

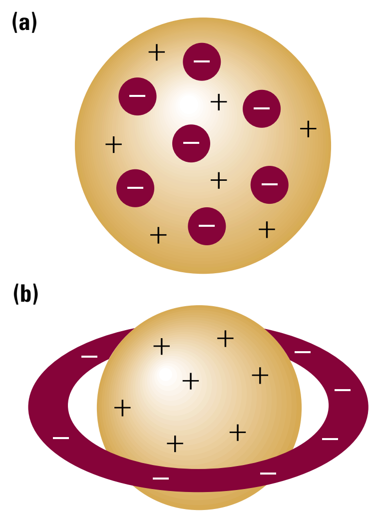

Figure 4
(a) In Thomson's model, the atom is a positive sphere with embedded electrons. This can be compared to a raisin bun in which the raisins represent the negative electrons and the bun represents the region of positive charge.
(b) In Nagaoka's model, the atom can be compared to the planet Saturn, where the planet represents the positively charged part of the atom, and the rings represent the negatively charged electrons.

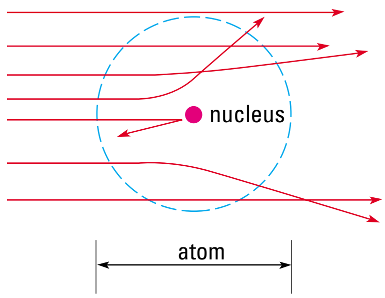

Figure 6
To explain the results of his experiment, Rutherford suggested that an atom consisted mostly of empty space, and that most of the alpha particles passed nearly straight through the gold foil because these particles did not pass close to a nucleus.

Table 1: Relative Masses and Charges of Subatomic Particles

Particle	Relative mass	Relative charge
electron	1	1–
proton	1836.12	1+
neutron	1838.65	0

Practice

Understanding Concepts

1. What is the difference between
   (a) a theory and a law?
   (b) empirical knowledge and theoretical knowledge?
2. Why is it useful for scientists to develop models of their ideas?
3. When wood is burned in a fireplace, its mass decreases. Does this observation contradict the law of conservation of mass? Justify your answer.
4. Draw a series of at least four diagrams to represent changing models of the atom, from the time of Democritus to 1932.
5. By 1932, Chadwick had modified Rutherford's model of the atom to include neutrons. According to this modified model, define each of the following:
   (a) nucleus
   (b) proton
   (c) electron
   (d) neutron

Making Connections

6. Research and describe some current technologies that have developed from or are related to cathode ray tubes.

DID YOU KNOW ?

Tiny but Massive

The word "massive" is used in everyday language to mean "very big," "huge," "enormous." In science it has a slightly different meaning: "having a relatively large mass for its size." So, a tiny nucleus can be massive, but an enormous hot-air balloon cannot!

1.3 Understanding Atomic Mass

atomic number (*Z*): the number of protons present in the nucleus of an atom of a given element

The number of protons in the nucleus determines the identity of an element and is referred to as that element's **atomic number** (**Z**). The concept of atomic number was developed by H.G.J. Moseley (1887–1915), an English physicist, subsequent to the results of Rutherford's alpha particle scattering experiments. Moseley's research work with X rays showed that the nucleus of each element has its own, unique positive charge. This positive charge increases by one as we progress, element by element, through Mendeleev's periodic table. Moseley was the first to recognize the relationship between atomic number and nuclear charge: They are equal. This discovery provided new insight into the periodic table and a rationale for listing the elements in order of the number of protons in the nucleus. Since atoms are electrically neutral, the atomic number also represents the number of electrons in an atom of an element.

By 1932, scientists had determined that the nucleus consists of protons (which are positively charged) and neutrons (which are neutral). Since both neutrons and protons are much more massive than electrons, and both reside in the nucleus, the mass of the atom is related to the number of nuclear particles (pro-