CHAPTER 3. BUILDING BLOCKS OF MATTER

Enhanced Introductory College Chemistry

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Chapter Contents

Please visit the web version of Enhanced Introductory College Chemistry (https://ecampusontario.pressbooks.pub/enhancedchemistry/) to access the complete book, interactive activities and ancillary resources.

In this chapter, you will learn about

- Elements and ions
- Chemical symbols
- The periodic table

- Ionic and molecular compounds
- Chemical formulas

To better support your learning, you should be familiar with the following concepts before starting this chapter:

- Numeracy

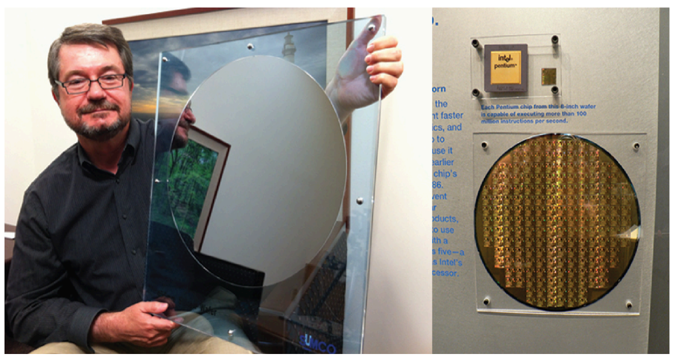

Figure 3a Purity is extremely important when preparing silicon wafers. The CEO of VLSI Research, Don Hutcheson, shows off a pure silicon wafer (left). A silicon wafer covered in Pentium chips is an enlarged version of the silicon wafers found in many electronics used today (right). (credit left: modification of work by Intel Free Press, CC BY 2.0; credit right: modification of work by Naotake Murayama (https://www.flickr.com/people/12832970@N00), CC BY 2.0)

The development of the periodic table in the mid-1800s came from observations that there was a periodic relationship between the properties of the elements. Chemists, who have an understanding of the variations of these properties, have been able to use this knowledge to solve a wide variety of technical challenges. For example, silicon and other semiconductors form the backbone of modern electronics because of our ability to fine-tune the electrical properties of these materials. This chapter explores important properties of representative metals, metalloids, and nonmetals in the periodic table.

Attributions & References

3.1 ELEMENTS

Learning Objectives

By the end of this section, you will be able to:

- Write and interpret symbols that depict the element

Chemical Symbols

A **chemical symbol** is an abbreviation that we use to indicate an element or an atom of an element. For example, the symbol for mercury is Hg (Figure 3.1a). We use the same symbol to indicate one atom of mercury (microscopic domain) or to label a container of many atoms of the element mercury (macroscopic domain).

Figure 3.1a The symbol Hg represents the element mercury regardless of the amount; it could represent one atom of mercury or a large amount of mercury. (credit: work by A, PD)

The symbols for several common elements and their atoms are listed in Table 3.1a Some symbols are derived from the common name of the element; others are abbreviations of the name in another language. Most symbols have one or two letters, but three-letter symbols have been used to describe some elements that have atomic numbers greater than 112. To avoid confusion with other notations, only the first letter of a symbol is capitalized. For example, Co is the symbol for the element cobalt, but CO is the notation for the compound carbon monoxide, which contains atoms of the elements carbon (C) and oxygen (O). All known elements and their symbols are in the periodic table Figure 3.1c.

Table 3.1a Some Common Elements and Their Symbols

Element	Symbol	Element	Symbol
aluminum	Al	iron	Fe (from *ferrum*)
bromine	Br	lead	Pb (from *plumbum*)
calcium	Ca	magnesium	Mg
carbon	C	mercury	Hg (from *hydrargyrum*)
chlorine	Cl	nitrogen	N
chromium	Cr	oxygen	O
cobalt	Co	potassium	K (from *kalium*)
copper	Cu (from *cuprum*)	silicon	Si
fluorine	F	silver	Ag (from *argentum*)
gold	Au (from *aurum*)	sodium	Na (from *natrium*)
helium	He	sulfur	S
hydrogen	H	tin	Sn (from *stannum*)
iodine	I	zinc	Zn

Traditionally, the discoverer (or discoverers) of a new element names the element. However, until the name is recognized by the International Union of Pure and Applied Chemistry (IUPAC), the recommended name of the new element is based on the Latin word(s) for its atomic number. For example, element 106 was called unnilhexium (Unh), element 107 was called unnilseptium (Uns), and element 108 was called unniloctium (Uno) for several years. These elements are now named after scientists (or occasionally locations); for example, element 106 is now known as *seaborgium* (Sg) in honour of Glenn Seaborg, a Nobel Prize winner who was active in the discovery of several heavy elements.

Scientists in Action: Marguerite Perey, PhD.

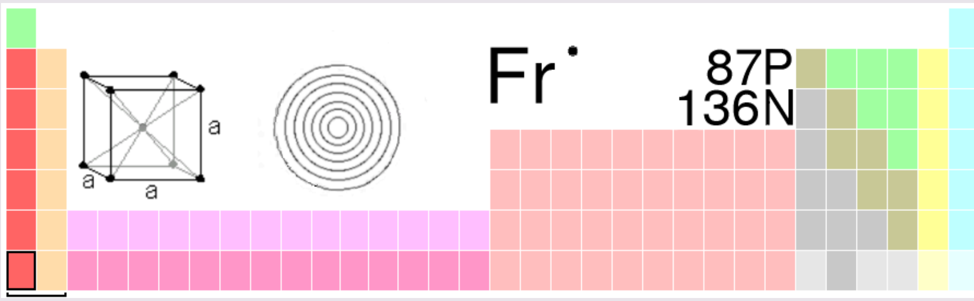

Figure 3.1b Francium (credit: work by Ahoerstemeier, CC BY-SA 3.0)

The discovery of the element 87 on the periodic table is thanks to Marguerite Perey, a French woman scientist. The story of the discovery of element 87, known as Francium, can be found on the Royal Society of Chemistry [New Tab] (https://www.chemistryworld.com/culture/marguerite-perey-and-the-last-element-in-nature/4012198.article) website. Marguerite Perey was nominated five times for a Nobel Prize but never received one.

Source: Chapman, K. (2020, August 3). Marguerite Perey and the last element in nature. *Chemistry World*. https://www.chemistryworld.com/culture/marguerite-perey-and-the-last-element-in-nature/4012198.article

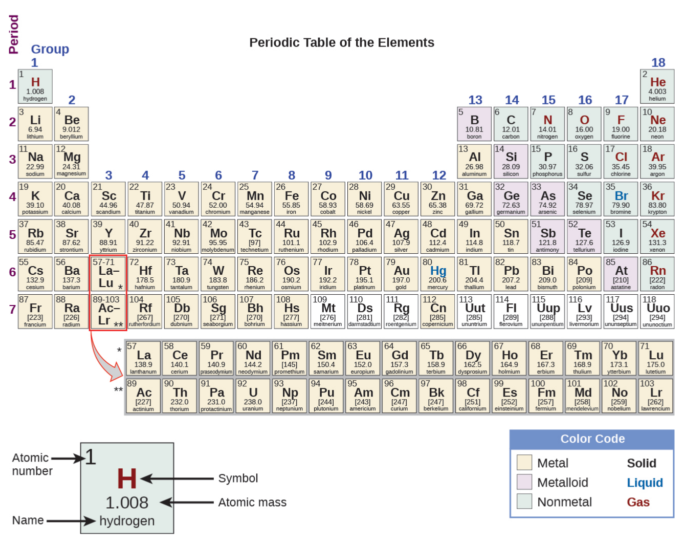

Figure 3.1c Elements and their symbols in the periodic table. Review the Periodic Table of the Elements in other formats in Appendix A (credit: *Chemistry (OpenStax)*, CC BY 4.0).

Exercise 3.1a

Check Your Learning Exercise (Text Version)
For each of the following elements listed, write the element's symbol.

a. Magnesium
b. Copper
c. Chlorine
d. Gold
e. Silicon
f. Potassium
g. Iron
h. Tungsten

Check Your Answer[1]

Source: "Exercise 3.1a" by Samantha Sullivan Sauer licensed under CC 4.0.

Links to Interactive Learning Tools

Visit the IUPAC, the International Union of Pure and Applied Chemistry (https://iupac.org/) website to learn more about IUPAC, and explore its periodic table (https://iupac.org/what-we-do/periodic-table-of-elements/).

Practice Name That Element (https://www.physicsclassroom.com/Concept-Builders/Chemistry/Name-That-Element) from the Physics Classroom (https://www.physicsclassroom.com/).

Attribution & References

Except where otherwise noted, this page is adapted by Adrienne Richards from "2.3 Atomic Structure and Symbolism" In *General Chemistry 1 & 2* by Rice University, a derivative of *Chemistry (Open Stax)* by Paul Flowers, Klaus Theopold, Richard Langley & William R. Robinson and is licensed under CC BY 4.0.

Notes

1. (a) Mg; (b) Cu; (c) Cl; (d) Au; (e) Si; (f) K; (g) Fe; (h) W;

3.2 THE PERIODIC TABLE

Learning Objectives

By the end of this section, you will be able to:

- State the periodic law and explain the organization of elements in the periodic table
- Predict the general properties of elements based on their location within the periodic table
- Identify metals, nonmetals, and metalloids by their properties and/or location on the periodic table

The Periodic Table

As early chemists worked to purify ores and discovered more elements, they realized that various elements could be grouped together by their similar chemical behaviours. One such grouping includes lithium (Li), sodium (Na), and potassium (K): These elements all are shiny, conduct heat and electricity well, and have similar chemical properties. A second grouping includes calcium (Ca), strontium (Sr), and barium (Ba), which also are shiny, good conductors of heat and electricity, and have chemical properties in common. However, the specific properties of these two groupings are notably different from each other. For example: Li, Na, and K are much more reactive than are Ca, Sr, and Ba; Li, Na, and K form compounds with oxygen in a ratio of two of their atoms to one oxygen atom, whereas Ca, Sr, and Ba form compounds with one of their atoms to one oxygen atom. Fluorine (F), chlorine (Cl), bromine (Br), and iodine (I) also exhibit similar properties to each other, but these properties are drastically different from those of any of the elements above.

Dimitri Mendeleev in Russia (1869) and Lothar Meyer in Germany (1870) independently recognized that there was a periodic relationship among the properties of the elements known at that time. Both published tables with the elements arranged according to increasing atomic mass. But Mendeleev went one step further than Meyer: He used his table to predict the existence of elements that would have the properties similar to aluminum and silicon, but were yet unknown. The discoveries of gallium (1875) and germanium (1886) provided great support for Mendeleev's work. Although Mendeleev and Meyer had a long dispute over priority, Mendeleev's contributions to the development of the periodic table are now more widely recognized (Figure 3.2a).

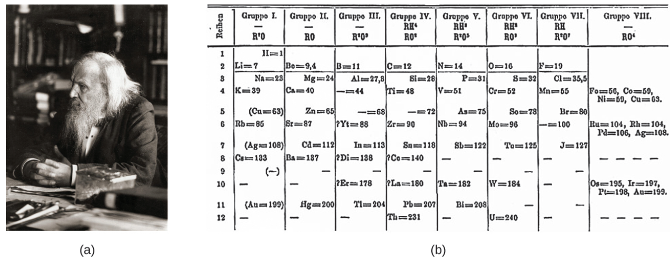

Figure 3.2a (a) Dimitri Mendeleev is widely credited with creating (b) the first periodic table of the elements. (credit a: modification of work by Serge Lachinov, PD; credit b: modification of work by Den fjättrade ankan, PD)

By the twentieth century, it became apparent that the periodic relationship involved atomic numbers rather than atomic masses. The modern statement of this relationship, the **periodic law**, is as follows: *the properties of the elements are periodic functions of their atomic numbers*. A modern **periodic table** arranges the elements in increasing order of their atomic numbers and groups atoms with similar properties in the same vertical column (Figure 3.2b). Each box represents an element and contains its atomic number, symbol, average atomic mass, and (sometimes) name. The elements are arranged in seven horizontal rows, called **periods** or **series**, and 18 vertical columns, called **groups**. Groups are labeled at the top of each column. In the United States, the labels traditionally were numerals with capital letters. However, IUPAC recommends that the numbers 1 through 18 be used, and these labels are more common. For the table to fit on a single page, parts of two of the rows, a total of 14 columns, are usually written below the main body of the table.

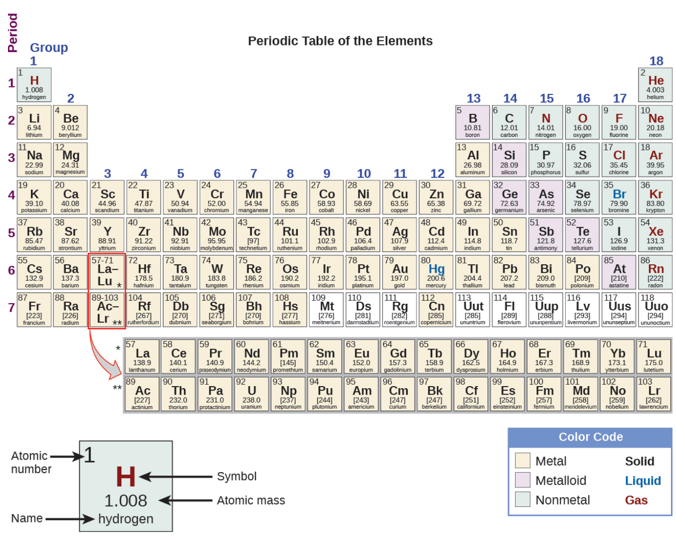

Figure 3.2b Elements in the periodic table are organized according to their properties. Review the Periodic Table of the Elements in other formats in Appendix A (credit: *Chemistry (OpenStax)*, CC BY 4.0).

Watch The Periodic Table Song (2018 Update!) (3:04 mins) (https://www.youtube.com/watch?v=rz4Dd1I_fX0)

Many elements differ dramatically in their chemical and physical properties, but some elements are similar in their behaviours. For example, many elements appear shiny, are malleable (able to be deformed without breaking) and ductile (can be drawn into wires), and conduct heat and electricity well. Other elements are not shiny, malleable, or ductile, and are poor conductors of heat and electricity. We can sort the elements into large classes with common properties: **metals** (elements that are shiny, malleable, good conductors of heat and electricity—shaded yellow); **nonmetals** (elements that appear dull, poor conductors of heat and electricity—shaded green); and **metalloids** (elements that conduct heat and electricity moderately well, and possess some properties of metals and some properties of nonmetals—shaded purple).

Metals

Most of the representative metals do not occur naturally in an uncombined state because they readily react with water and oxygen in the air. However, it is possible to isolate elemental beryllium, magnesium, zinc, cadmium, mercury, aluminum, tin, and lead from their naturally occurring minerals and use them because they react very slowly with air. Part of the reason why these elements react slowly is that these elements react with air to form a protective coating. The formation of this protective coating is **passivation**. The coating is a nonreactive film of oxide or some other compound. Elemental magnesium, aluminum, zinc, and tin are important in the fabrication of many familiar items, including wire, cookware, foil, and many household and personal objects. Although beryllium, cadmium, mercury, and lead are readily available, there are limitations in their use because of their toxicity.

Mercury – An Interesting Metal

Mercury is the only metal that is liquid at 25 °C. Many metals dissolve in mercury, forming solutions called amalgams (see the feature on Amalgams), which are alloys of mercury with one or more other metals. Mercury, shown in Figure 3.2c, is a nonreactive element that is more difficult to oxidize than hydrogen. Thus, it does not displace hydrogen from acids; however, it will react with strong oxidizing acids, such as nitric acid:

$$\mathrm{Hg}(l) \;+\; \mathrm{HCl}(aq) \longrightarrow \text{no reaction}$$

$$3\mathrm{Hg}(l) \;+\; 8\mathrm{HNO_3}(aq) \longrightarrow 3\mathrm{Hg(NO_3)_2}(aq) \;+\; 4\mathrm{H_2O}(l) \;+\; 2\mathrm{NO}(g)$$

The clear NO initially formed quickly undergoes further oxidation to the reddish brown NO_2.

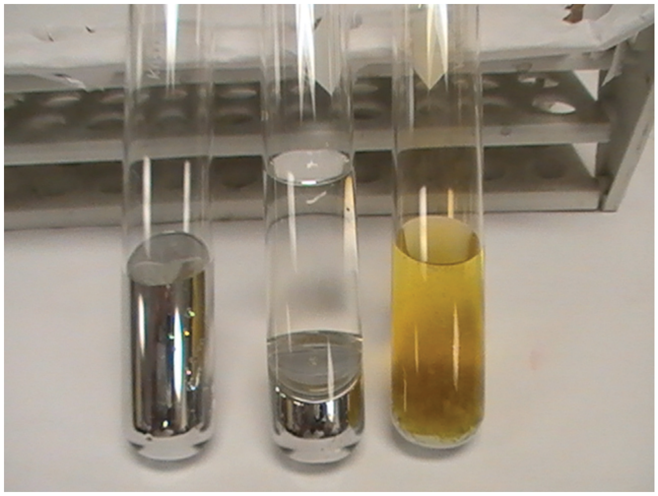

Figure 3.2c From left to right: Hg(*l*), Hg + concentrated HCl, Hg + concentrated HNO_3. (credit: Sahar Atwa in *Chemistry (OpenStax)*, CC BY 4.0).

Amalgams

An amalgam is an alloy of mercury with one or more other metals. This is similar to considering steel to be an alloy of iron with other metals. Most metals will form an amalgam with mercury, with the main exceptions being iron, platinum, tungsten, and tantalum.

Due to toxicity issues with mercury, there has been a significant decrease in the use of amalgams. Historically, amalgams were important in electrolytic cells and in the extraction of gold. Amalgams of the alkali metals still find use because they are strong reducing agents and easier to handle than the pure alkali metals.

Prospectors had a problem when they found finely divided gold. They learned that adding mercury to their pans collected the gold into the mercury to form an amalgam for easier collection. Unfortunately, losses of small amounts of mercury over the years left many streams in California polluted with mercury.

Dentists use amalgams containing silver and other metals to fill cavities. There are several reasons to use an amalgam including low cost, ease of manipulation, and longevity compared to alternate materials. Dental amalgams are approximately 50% mercury by weight, which, in recent years, has become a concern due to the toxicity of mercury.

After reviewing the best available data, the Food and Drug Administration (FDA) considers amalgam-based fillings to be safe for adults and children over six years of age. Even with multiple fillings, the mercury levels in the patients remain far below the lowest levels associated with harm. Clinical studies have found no link between dental amalgams and health problems. Health issues may not be the same in cases of children under six or pregnant women. The FDA conclusions are in line with the opinions of the Environmental Protection Agency (EPA) and Centres for Disease Control (CDC). The only health consideration noted is that some people are allergic to the amalgam or one of its components.

Nonmetals

The nonmetals are elements located in the upper right portion of the periodic table. Their properties and behaviour are quite different from those of metals on the left side. Under normal conditions, more than half of the nonmetals are gases, one is a liquid, and the rest include some of the softest and hardest of solids. The nonmetals exhibit a rich variety of chemical behaviours. They include the most reactive and least reactive of elements, and they form many different ionic and covalent compounds.

Carbon – An Interesting Nonmetal

Carbon occurs in the uncombined (elemental) state in many forms, such as diamond, graphite, charcoal, coke, carbon black, graphene, and fullerene.

Diamond, shown in Figure 3.2d, is a very hard crystalline material that is colourless and transparent when pure. Each atom forms four single bonds to four other atoms at the corners of a tetrahedron (sp^3 hybridization); this makes the diamond a giant molecule. Carbon-carbon single bonds are very strong, and, because they extend throughout the crystal to form a three-dimensional network, the crystals are very hard and have high melting points (~4400 °C).

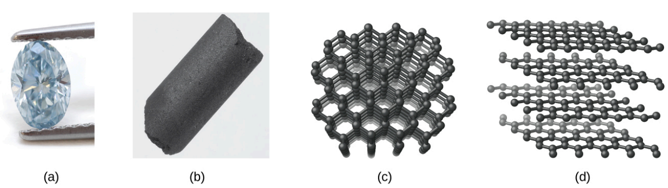

Figure 3.2d (a) Diamond and (b) graphite are two forms of carbon. (c) In the crystal structure of diamond, the covalent bonds form three-dimensional tetrahedrons. (d) In the crystal structure of graphite, each planar layer is composed of six-membered rings. (credit a: modification of work by Fancy Diamonds, CC BY 2.0; credit b: modification of work by Anonymous, CC BY 3.0, credit c, d: *Chemistry (OpenStax)*, CC BY 4.0).

Metalloids

A series of six elements called the metalloids separate the metals from the nonmetals in the periodic table. The metalloids are boron, silicon, germanium, arsenic, antimony, and tellurium. These elements look metallic; however, they do not conduct electricity as well as metals so they are semiconductors. They are semiconductors because their electrons are more tightly bound to their nuclei than are those of metallic conductors. Their chemical behaviour falls between that of metals and nonmetals. For example, the pure metalloids form covalent crystals like the nonmetals, but like the metals, they generally do not form monatomic anions. This intermediate behaviour is in part due to their intermediate electronegativity values.

Boron and Silicon – Two Interesting Metalloids

Boron constitutes less than 0.001% by weight of the earth's crust. In nature, it only occurs in compounds with oxygen. Boron is widely distributed in volcanic regions as boric acid, $B(OH)_3$, and in dry lake regions, including the desert areas of California, as borates and salts of boron oxyacids, such as borax, $Na_2B_4O_7{\cdot}10H_2O$. Silicon makes up nearly one-fourth of the mass of the earth's crust—second in abundance only to oxygen. Extremely pure silicon is necessary for the manufacture of semiconductor electronic devices.

Boron burns at 700 °C in oxygen, forming boric oxide, B_2O_3. Boric oxide is necessary for the production of heat-resistant borosilicate glass, like that shown in Figure 3.2e and certain optical glasses. Boric oxide dissolves in hot water to form boric acid, $B(OH)_3$:

$$\mathrm{B_2O_3}(s) \ + \ 3\mathrm{H_2O}(l) \longrightarrow 2\mathrm{B(OH)_3}(aq)$$

Figure 3.2e Laboratory glassware, such as Pyrex and Kimax, is made of borosilicate glass because it does not break when heated. The inclusion of borates in the glass helps to mediate the effects of thermal expansion and contraction. This reduces the likelihood of thermal shock, which causes silicate glass to crack upon rapid heating or cooling. (credit: photo by Tweenk, CC BY 3.0)

When silicon reacts with oxygen, silicon dioxide is formed. Silicon dioxide, silica, occurs in both crystalline and amorphous forms. The usual crystalline form of silicon dioxide is quartz, a hard, brittle, clear, colourless solid. It is useful in many ways—for architectural decorations, semiprecious jewels, and frequency control in radio transmitters. Silica takes many crystalline forms, or **polymorphs**, in nature. Trace amounts of Fe^{3+} in quartz give amethyst its characteristic purple colour. The term *quartz* is also used for articles such as tubing and lenses that are manufactured from amorphous silica. Opal is a naturally occurring form of amorphous silica.

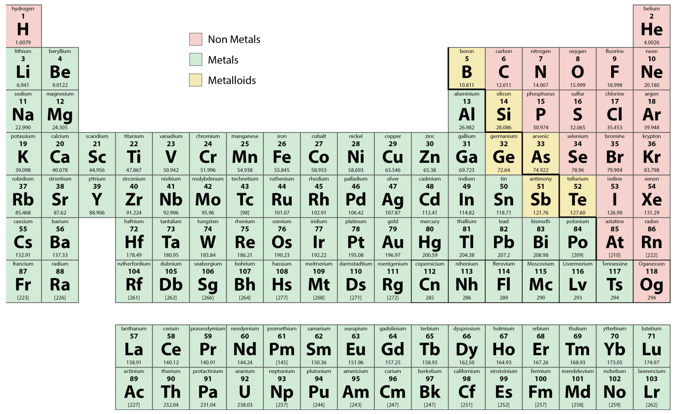

Figure 3.2f Metals, non-metals, and metalloids in the periodic table. (credit: graphic by Revathi Mahadevan, CC BY 4.0) Review the Periodic Table of the Elements in other formats in Appendix A.

The Organization of the Periodic Table

The elements can also be classified into the **main-group elements** (or **representative elements**) in the columns labeled 1, 2, and 13–18; the **transition metals** in the columns labeled 3–12; and **inner transition metals** in the two rows at the bottom of the table (the top-row elements are called **lanthanides** and the bottom-row elements are **actinides**; Figure 3.2f). The elements can be subdivided further by more specific properties, such as the composition of the compounds they form. For example, the elements in group 1 (the first column) form compounds that consist of one atom of the element and one atom of hydrogen. These elements (except hydrogen) are known as **alkali metals**, and they all have similar chemical properties. The elements in group 2 (the second column) form compounds consisting of one atom of the element and two atoms of hydrogen: These are called **alkaline earth metals**, with similar properties among members of that group. Other groups with specific names are the **pnictogens** (group 15), **chalcogens** (group 16), **halogens** (group 17), and the **noble gases** (group 18, also known as **inert gases**). The groups can also be referred to by the first element of the group: For example, the chalcogens can be called the oxygen group or oxygen family. Hydrogen is a unique, nonmetallic element with properties similar to both group 1A and group 7A elements. For that reason, hydrogen may be shown at the top of both groups, or by itself.

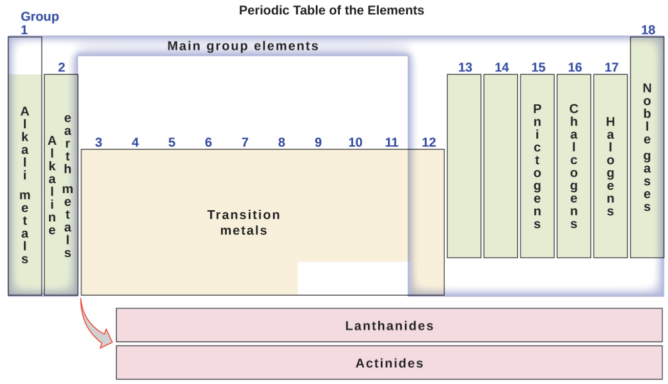

Figure 3.2g The periodic table organizes elements with similar properties into groups. Review the Periodic Table of the Elements in other formats in Appendix A (credit: *Chemistry (OpenStax)*, CC BY 4.0).

Group 1: The Alkali Metals

The alkali metals lithium, sodium, potassium, rubidium, cesium, and francium constitute group 1 of the periodic table. Although hydrogen is in group 1, it is a nonmetal. The name alkali metal is in reference to the fact that these metals and their oxides react with water to form very basic (alkaline) solutions.

The properties of the alkali metals are similar to each other as expected for elements in the same family. The alkali metals have the largest atomic radii and the lowest first ionization energy in their periods. This combination makes it very easy to remove the single electron in the outermost (valence) shell of each. The easy loss of this valence electron means that these metals readily form stable cations with a charge of 1+. Their reactivity increases with the increasing atomic number due to the ease of losing the lone valence electron (decreasing ionization energy).

The alkali metals all react vigorously with water to form hydrogen gas and a basic solution of the metal hydroxide.

Group 2: The Alkaline Earth Metals

The **alkaline earth metals** (beryllium, magnesium, calcium, strontium, barium, and radium) constitute group 2 of the periodic table. The name alkaline metal comes from the fact that the oxides of the heavier members of the group react with water to form alkaline solutions. The nuclear charge increases when going from group 1 to group 2. Because of this charge increase, the atoms of the alkaline earth metals are smaller and have higher first ionization energies than the alkali metals within the same period. The higher ionization energy makes the alkaline earth metals less reactive than the alkali metals; however, they are still very reactive elements. Their reactivity increases, as expected, with increasing size and decreasing ionization energy. In chemical reactions, these metals readily lose both valence electrons to form compounds in which they exhibit an oxidation state of 2+.

Groups 7 and 8: Halogens and Noble Gases

The noble gases are all monatomic, whereas the other nonmetal gases—hydrogen, nitrogen, oxygen, fluorine, and chlorine—normally exist as the diatomic molecules H_2, N_2, O_2, F_2, and Cl_2. The other halogens are also diatomic; Br_2 is a liquid and I_2 exists as a solid under normal conditions.

Halogens

Halogens are found in group 17 (or 7A) within the periodic table. These include Fluorine, Chlorine, Bromine and Iodine. Fluorine is a pale yellow gas, chlorine is a greenish-yellow gas, bromine is a deep reddish-brown liquid, and iodine is a grayish-black crystalline solid. Liquid bromine has a high vapour pressure, and the reddish vapour is readily visible in Figure 3.2g. Iodine crystals have a noticeable vapour pressure. When gently heated, these crystals sublime and form a beautiful deep violet vapour.

Figure 3.2h Chlorine is a pale yellow-green gas (left), gaseous bromine is deep orange (centre), and gaseous iodine is purple (right). (Fluorine is so reactive that it is too dangerous to handle.) (credit: Sahar Atwa in *Chemistry (OpenStax)*, CC BY 4.0).

The Noble Gases

The elements in group 18 (or 8A) are the noble gases (helium, neon, argon, krypton, xenon, and radon). They earned the name "noble" because they were assumed to be nonreactive since they filled valence shells. In 1962, Dr. Neil Bartlett at the University of British Columbia proved this assumption to be false.

These elements are present in the atmosphere in small amounts. Some natural gas contains 1–2% helium by mass. Helium is isolated from natural gas by liquefying the condensable components, leaving only helium as a gas. The United States possesses most of the world's commercial supply of this element in its helium-bearing gas fields. Argon, neon, krypton, and xenon come from the fractional distillation of liquid air. Radon comes from other radioactive elements. More recently, it was observed that this radioactive gas is present in very small amounts in soils and minerals. Its accumulation in well-insulated, tightly sealed buildings, however, constitutes a health hazard, primarily lung cancer.

Exercise 3.2a

Check Your Learning Exercise (Text Version)

Atoms of elements are essential for life. Identify the group name (Alkali Metal, Gas, **Chalcogen**, Alkaline Earth Metal, Halogen) that each of the following elements belong to:

a. chlorine belongs to
b. calcium and barium belongs to
c. sodium and lithium belongs to
d. sulfur and selenium belongs to
e. krypton belongs to

Check Your Answer[1]

Source: "Exercise 3.1a" is adapted from "3.6 The Periodic Table Example 1" from General Chemistry 1 & 2, a derivative of Chemistry (Open Stax) by Paul Flowers, Klaus Theopold, Richard Langley & William R. Robinson, licensed under CC BY 4.0.

In studying the periodic table, you might have noticed something about the atomic masses of some of the elements. Element 43 (technetium), element 61 (promethium), and most of the elements with atomic number 84 (polonium) and higher have their atomic mass given in square brackets. This is done for elements that consist entirely of unstable, radioactive isotopes (you will learn more about radioactivity in the nuclear chemistry chapter). An average atomic weight cannot be determined for these elements because their radioisotopes may vary significantly in relative abundance, depending on the source, or may not even exist in nature. The number in square brackets is the atomic mass number (and approximate atomic mass) of the most stable isotope of that element.

Links to Interactive Learning Tools

Click on the interactive periodic table (http://openstaxcollege.org/l/16Periodic), from the Royal Society of Chemistry (https://www.rsc.org/), which you can use to explore the properties of the elements (includes podcasts and videos of each element).

Classify Metals, Metalloids and Nonmetals (https://www.physicsclassroom.com/Concept-Builders/Chemistry/Metals-and-Nonmetals) from the Physics Classroom (https://www.physicsclassroom.com/).

Explore the Classification of Matter (https://www.physicsclassroom.com/Concept-Builders/Chemistry/Classifications-of-Matter) from the Physics Classroom (https://www.physicsclassroom.com/).

Explore Elements, Atoms, and Ions Practice (https://h5pstudio.ecampusontario.ca/content/16421) from eCampusOntario H5P Studio (https://h5pstudio.ecampusontario.ca/).

Make a New Periodic Table (https://h5pstudio.ecampusontario.ca/content/16196) from eCampusOntario H5P Studio (https://h5pstudio.ecampusontario.ca/).

Attribution & References

Notes

1. (a) Halogen; (b) Alkaline Earth Metal; (c) Alkali Metal; (d) Chalcogen; (e) Gas

3.3 COMPOUNDS AND FORMULAS

Learning Objectives

By the end of this section, you will be able to:

- Define molecular and structural formulas
- Define ionic and molecular (covalent) compounds
- Determine the number of atoms of each element in a compound

Chemical Formulae

A **molecular formula** is a representation of a molecule that uses chemical symbols to indicate the types of atoms followed by subscripts to show the number of atoms of each type in the molecule. (A subscript is used only when more than one atom of a given type is present.) Molecular formulas are also used as abbreviations for the names of compounds.

The **structural formula** for a compound gives the same information as its molecular formula (the types and numbers of atoms in the molecule) but also shows how the atoms are connected in the molecule. The structural formula for methane contains symbols for one C atom and four H atoms, indicating the number of atoms in the molecule (Figure 3.3a). The lines represent bonds that hold the atoms together. (A chemical bond is an attraction between atoms or ions that holds them together in a molecule or a crystal.) We will discuss chemical bonds and see how to predict the arrangement of atoms in a molecule later. For structural formula now, simply know that the lines are an indication of how the atoms are connected in a molecule. A ball-and-stick model shows the geometric arrangement of the atoms with atomic sizes not to scale, and a space-filling model shows the relative sizes of the atoms.

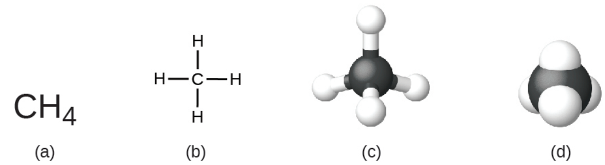

Figure 3.3a A methane molecule can be represented as (a) a molecular formula, (b) a structural formula, (c) a ball-and-stick model, and (d) a space-filling model. Carbon and hydrogen atoms are represented by black and white spheres, respectively (credit: *Chemistry (OpenStax),* CC BY 4.0).

Although many elements consist of discrete, individual atoms, some exist as molecules made up of two or more atoms of the element chemically bonded together. For example, most samples of the elements hydrogen, oxygen, and nitrogen are composed of molecules that contain two atoms each (called **diatomic molecules**) and thus have the molecular formulas H_2, O_2, and N_2, respectively. Other elements commonly found as diatomic molecules are fluorine (F_2), chlorine (Cl_2), bromine (Br_2), and iodine (I_2). The most common form of the element sulfur is composed of molecules that consist of eight atoms of sulfur; its molecular formula is S_8 (Figure 3.3b).

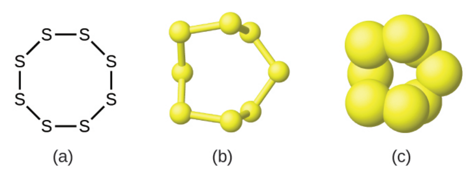

Figure 3.3b A molecule of sulfur is composed of eight sulfur atoms and is therefore written as S_8. It can be represented as (a) a structural formula, (b) a ball-and-stick model, and (c) a space-filling model. Sulfur atoms are represented by yellow spheres (credit: *Chemistry (OpenStax),* CC BY 4.0).

It is important to note that a subscript following a symbol and a number in front of a symbol do not represent the same thing; for example, H_2 and 2H represent distinctly different species. H_2 is a molecular formula; it represents a diatomic molecule of hydrogen, consisting of two atoms of the element that are chemically bonded together. The expression 2H, on the other hand, indicates two separate hydrogen atoms that are not combined as a unit. The expression $2H_2$ represents two molecules of diatomic hydrogen (Figure 3.3c.).

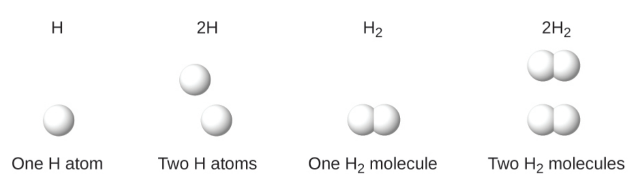

Figure 3.3c The symbols H, 2H, H_2, and $2H_2$ represent very different entities (credit: *Chemistry (OpenStax),* CC BY 4.0).

Compounds are formed when two or more elements chemically combine, resulting in the formation of bonds. For example, hydrogen and oxygen can react to form water, and sodium and chlorine can react to form table salt.

As discussed previously, we can describe a compound with a molecular formula, in which the subscripts indicate the *actual numbers of atoms* of each element in a molecule of the compound. For example, it can be determined experimentally that benzene contains two elements, carbon (C) and hydrogen (H), and that for every carbon atom in benzene, there is one hydrogen atom. An experimental determination of the molecular mass reveals that a molecule of benzene contains six carbon atoms and six hydrogen atoms, so the molecular formula for benzene is C_6H_6 (Figure 3.3d).

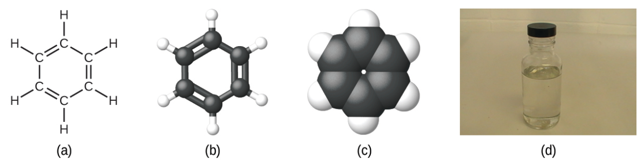

Figure 3.3d Benzene, C_6H_6, is produced during oil refining and has many industrial uses. A benzene molecule can be represented as (a) a structural formula, (b) a ball-and-stick model, and (c) a space-filling model. (d) Benzene is a clear liquid. (credit d: modification of work by Sahar Atwa in *Chemistry (OpenStax)*, CC BY 4.0)

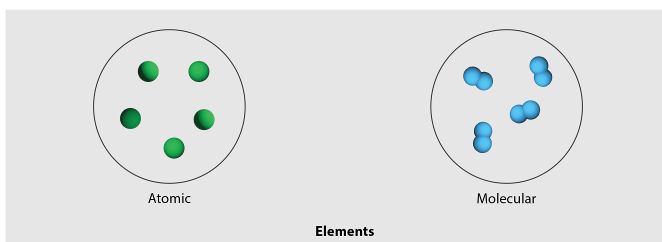

Figure 3.3e The figure illustrates the difference in the atomic structure of an element. (credit: modification of work by Hoa112008, PD; / Adapted by Revathi Mahadevan, CC BY 4.0).

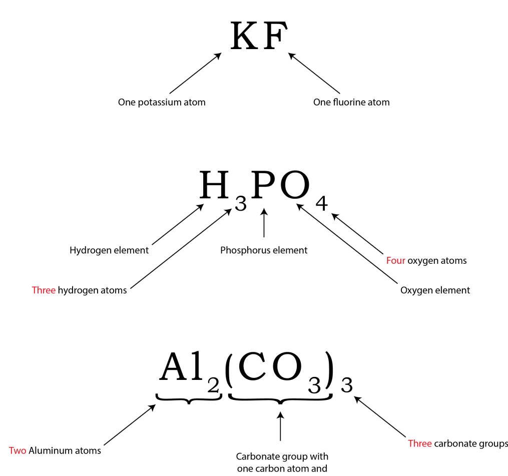

Figure 3.3f Breakdown of compounds. (credit: graphic by Revathi Mahadevan, CC BY 4.0)

Example 3.3a

Molecular Formulas

Molecules of glucose (blood sugar) contain 6 carbon atoms, 12 hydrogen atoms, and 6 oxygen atoms. What is the molecular formula of glucose?

Solution

The molecular formula is $C_6H_{12}O_6$ because one molecule actually contains 6 C, 12 H, and 6 O atoms.

Exercise 3.3a

A molecule of metaldehyde (a pesticide used for snails and slugs) contains 8 carbon atoms, 16 hydrogen atoms, and 4 oxygen atoms. What is the molecular formula of metaldehyde?

Check Your Answer[1]

It is important to be aware that it may be possible for the same atoms to be arranged in different ways: Compounds with the same molecular formula may have different atom-to-atom bonding and therefore different structures.

Example 3.3b

Determine the number of atoms of each element and the total number of atoms for the compound $AlCl_3$?

Solution

1 Al atom

3 Cl atoms

Total number of atoms in $AlCl_3$ is 4 atoms since 1 Al atom + 3 Cl atoms = 4 total atoms

Source: "Example 3.3b" by Adrienne Richards is licensed under CC BY NC 4.0.

Example 3.3c

How many atoms of each element and the total number of atoms are present in the compound $CaCO_3$?

Answer

1 Ca

1 C

3 O

The total number of atoms in $CaCO_3$ is 5 since 1 Ca + 1 C + 3 O = 5 atoms.

Source: "Example 3.3c" by Adrienne Richards is licensed under CC BY NC 4.0.

The Formation of Chemical Compounds

In ordinary chemical reactions, the nucleus of each atom (and thus the identity of the element) remains unchanged. Electrons, however, can be added to atoms by transfer from other atoms, lost by transfer to other atoms, or shared with other atoms. The transfer and sharing of electrons among atoms govern the chemistry of the elements. During the formation of some compounds, atoms gain or lose electrons, and form electrically charged particles called **ions** (Figure 3.3e).

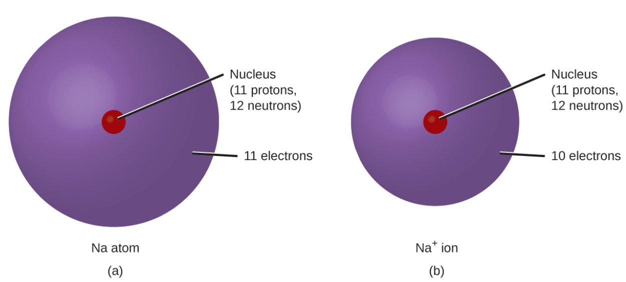

Figure 3.3g (a) A sodium atom (Na) has equal numbers of protons and electrons (11) and is uncharged. (b) A sodium cation (Na+) has lost an electron, so it has one more proton (11) than electrons (10), giving it an overall positive charge, signified by a superscripted plus sign (credit: *Chemistry (OpenStax)*, CC BY 4.0).

The nature of the attractive forces that hold atoms or ions together within a compound is the basis for classifying chemical bonding. When electrons are transferred and ions form, **ionic bonds** result. Ionic bonds are electrostatic forces of attraction, that is, the attractive forces experienced between objects of opposite electrical charge (in this case, **cations** and **anions**). When electrons are "shared" and molecules form, **covalent bonds** result. Covalent bonds are the attractive forces between the positively charged nuclei of the bonded atoms and one or more pairs of electrons that are located between the atoms. Compounds are classified as ionic or molecular (covalent) on the basis of the bonds present in them.

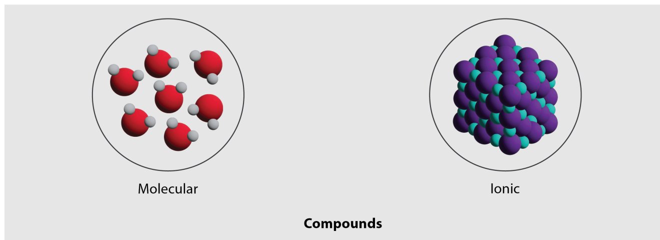

Figure 3.3h The figure illustrates the difference in atomic structure in a compound. (credit: graphic by Revathi Mahadevan, CC BY 4.0)

Ionic Compounds

When an element composed of atoms that readily lose electrons (a metal) reacts with an element composed of atoms that readily gain electrons (a nonmetal), a transfer of electrons usually occurs, producing ions. A compound that contains ions and is held together by ionic bonds is called an **ionic compound**. The periodic table can help us recognize many of the compounds that are ionic: When a metal is combined with one or more nonmetals, the compound is usually ionic.

Watch Conductivity molten salt (1 mins) (https://www.youtube.com/watch?v=ePzEVPDyJV8)

In every ionic compound, the total number of positive charges of the cations equals the total number of negative charges of the anions. Thus, ionic compounds are electrically neutral overall, even though they contain positive and negative ions. We can use this observation to help us write the formula of an ionic compound. The formula of an ionic compound must have a ratio of ions such that the numbers of positive and negative charges are equal.

Molecular Compounds

Many compounds do not contain ions but instead consist solely of discrete, neutral molecules. These **molecular compounds** (**covalent compounds**) result when atoms share, rather than transfer (gain or lose), electrons. Covalent bonding is an important and extensive concept in chemistry, and it will be treated in considerable detail in a later chapter of this text. We can often identify molecular compounds on the basis of their physical properties. Under normal conditions, molecular compounds often exist as gases, low-boiling liquids, and low-melting solids, although many important exceptions exist.

Whereas ionic compounds are usually formed when a metal and a nonmetal combine, covalent compounds are usually formed by a combination of nonmetals.

Scientists in Action: Dr. Uma Chowdhry

Figure 3.3i Dr. Uma Chowdhry (credit: Photo by Science History Institute, CC BY-SA 3.0)

Dr. Uma Chowdhry is a retired senior vice president and chief science and technology officer for DuPont, where she worked from 1977 to 2010. She was born in Mumbai, then came to the U.S. for her Masters Degree from Caltech and her PhD in material science from MIT.

Dr. Chowdhry started as a research scientist for Dupont and, throughout her career, she was responsible for overseeing a large number of projects. In 1987 the research efforts she led in ceramic superconducting materials generated over 20 patents and 50 publications.

There is a very good chance you own something that relies on materials and technology developed by DuPont during Dr. Chowdhry's time.

See Dr. Chowdhry talking more about her life in Women in Chemistry: Uma Chowdhry [New Tab] (https://www.youtube.com/watch?v=U-j5oFiue58).

Links to Interactive Learning Tools

Practice Chemical Formulas and Atom Counting (https://www.physicsclassroom.com/Concept-Builders/Chemistry/Atom-Counting) by the Physics Classroom (https://www.physicsclassroom.com/).

Attribution & References

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- "2.6 Ionic and Molecular Compounds" In *Chemistry 2e (OpenStax)* by Paul Flowers, Klaus Theopold, Richard Langley, & William R. Robinson, licensed under CC BY 4.0. / Adaptations include combining sections 2.4 and 2.6. Access for free at Chemistry 2e (OpenStax).

Notes

1. Molecular formula, $C_8H_{16}O_4$

CHAPTER 3 SUMMARY

3.1 Elements

A chemical symbol identifies the atoms in a substance using symbols, which are one-, two-, or three-letter abbreviations for the atoms. The chemical symbols represent the element found on the periodic table.

3.2 The Periodic Table

The discovery of the periodic recurrence of similar properties among the elements led to the formulation of the periodic table, in which the elements are arranged in order of increasing atomic number in rows known as periods and columns known as groups. Elements in the same group of the periodic table have similar chemical properties. Elements can be classified as metals, metalloids, and nonmetals, or as a main-group elements, transition metals, and inner transition metals. Groups are numbered 1–18 from left to right. The elements in group 1 are known as the alkali metals; those in group 2 are the alkaline earth metals; those in 15 are the pnictogens; those in 16 are the chalcogens; those in 17 are the halogens; and those in 18 are the noble gases.

Metals (particularly those in groups 1 and 2) tend to lose the number of electrons that would leave them with the same number of electrons as in the preceding noble gas in the periodic table. This means, a positively charged ion is formed. Similarly, nonmetals (especially those in groups 16 and 17, and, to a lesser extent, those in Group 15) can gain the number of electrons needed to provide atoms with the same number of electrons as in the next noble gas in the periodic table. Thus, nonmetals tend to form negative ions. Positively charged ions are called cations, and negatively charged ions are called anions. Ions can be either monatomic (containing only one atom) or polyatomic (containing more than one atom).

3.3 Compounds and Formulas

Compounds that contain ions are called ionic compounds. Ionic compounds generally form between metals and nonmetals. Compounds that do not contain ions, but instead consist of atoms bonded tightly together in molecules (uncharged groups of atoms that behave as a single unit), are called covalent compounds. Covalent compounds usually form from two nonmetals.

A molecular formula uses chemical symbols and subscripts to indicate the exact numbers of different atoms in a molecule or compound. A structural formula indicates the bonding arrangement of the atoms in the molecule.

Attribution & References

CHAPTER 3 REVIEW

3.1 Elements; and 3.2 The Periodic Table

1. Using the periodic table, classify each of the following elements as a metal or a nonmetal, and then further classify each as a main-group (representative) element, transition metal, or inner transition metal:
    a. uranium
    b. bromine
    c. strontium
    d. neon
    e. gold
    f. americium
    g. rhodium
    h. sulfur
    i. carbon
    j. potassium

    Check answers: [1]
2. Using the periodic table, classify each of the following elements as a metal or a nonmetal, and then further classify each as a main-group (representative) element, transition metal, or inner transition metal:
    a. cobalt
    b. europium
    c. iodine
    d. indium
    e. lithium
    f. oxygen
    g. cadmium
    h. terbium
    i. rhenium
3. Using the periodic table, identify the lightest member of each of the following groups:
    a. noble gases
    b. alkaline earth metals
    c. alkali metals

   d. chalcogens

      Check answers: [2]

4. Using the periodic table, identify the heaviest member of each of the following groups:
   a. alkali metals
   b. chalcogens
   c. noble gases
   d. alkaline earth metals
5. Use the periodic table to give the name and symbol for each of the following elements:
   a. the noble gas in the same period as germanium
   b. the alkaline earth metal in the same period as selenium
   c. the halogen in the same period as lithium
   d. the chalcogen in the same period as cadmium

      Check answers: [3]

3.3 Compounds and Formulas

1. Using the periodic table, predict whether the following chlorides are ionic or covalent: KCl, NCl_3, ICl, $MgCl_2$, PCl_5, and CCl_4.
   Check answers: [4]
2. Using the periodic table, predict whether the following chlorides are ionic or covalent: $SiCl_4$, PCl_3, $CaCl_2$, CsCl, $CuCl_2$, and $CrCl_3$.
3. For each of the following compounds, state whether it is ionic or covalent; write the number of atoms of each element in the compound and the total number of atoms present.
   a. NF_3
   b. BaO
   c. $(NH_4)_2CO_3$
   d. $Sr(H_2PO_4)_2$
   e. IBr
   f. Na_2O

      Check answers: [5]

4. For each of the following compounds, state whether it is ionic or covalent; write the number of atoms of each element in the compound and the total number of atoms present.
   a. $KClO_4$
   b. $MgC_2H_3O_2$
   c. H_2S
   d. Ag_2S
   e. N_2Cl_4

   f. $Co(NO_3)_2$

5. For each of the following pairs of ions, write the symbol for the formula of the compound they will form:
   a. Ca^{2+}, S^{2-}
   b. NH_4^+, SO_4^{2-}
   c. Al^{3+}, Br^-
   d. Na^+, HPO_4^{2-}
   e. Mg^{2+}, PO_4^{3-}

   Check answers:[6]
6. For each of the following pairs of ions, write the symbol for the formula of the compound they will form:
   a. K^+, O^{2-}
   b. NH_4^+, PO_4^{3-}
   c. Al^{3+}, O^{2-}
   d. Na^+, CO_3^{2-}
   e. Ba^{2+}, PO_4^{3-}

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Notes

1. (a) metal, inner transition metal; (b) nonmetal, representative element; (c) metal, representative element; (d) nonmetal, representative element; (e) metal, transition metal; (f) metal, inner transition metal; (g) metal, transition metal; (h) nonmetal, representative element; (i) nonmetal, representative element; (j) metal, representative
2. (a) He; (b) Be; (c) Li; (d) O
3. (a) krypton, Kr; (b) calcium, Ca; (c) fluorine, F; (d) tellurium, Te
4. 1. Ionic: KCl, $MgCl_2$; Covalent: NCl_3, ICl, PCl_5, CCl_4
5. (a) covalent; 1 Na, 3F, Total 4 atoms (b) ionic; 1 Ba, 1 O, Total 3 atoms (c) ionic; 2 N, 8H, 1 C, 3 O, Total 14 atoms (d) ionic; 1 Sr, 4 H, 2 P, 8 O, Total 15 atoms (e) covalent; 1 I , 1 Br, Total 2 atoms (f) ionic; 2 Na, 1 O, Total 3 atoms.
6. (a) CaS; (b) $(NH_4)_2SO_4$; (c) $AlBr_3$; (d) Na_2HPO_4; (e) $Mg_3(PO_4)_2$