2.12 The Law of Multiple Proportions

A third law that can be explained by atomic theory is John Dalton's **Law of Multiple Proportions**. When elements react to form compounds, they do so in small whole number ratios. For example, copper and oxygen react to form two simple compounds: copper(I) oxide (Cu_2O) and copper(II) oxide (CuO) (Figure 2.12). From elemental analysis, it is determined that there are 7.94 grams of copper per one gram of oxygen in copper(I) oxide and 3.97 grams of copper per one gram of oxygen in copper(II) oxide.

The ratio $\frac{7.94g}{3.97g}$ = 2.00. This ratio is the same as the ratio of the number of copper atoms: there are two copper atoms per oxygen atom in copper(I) oxide and one copper atom per oxygen atom in copper(II) oxide. Since two copper atoms have twice the mass of one copper atoms, the ratio of the masses of copper in the two compounds must be 2:1.

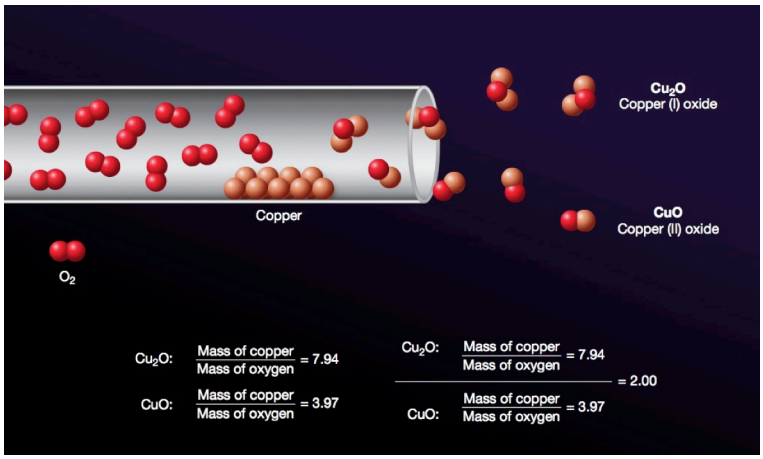
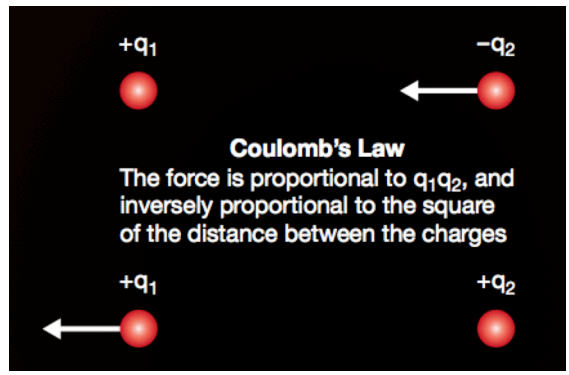


Figure 2.12 Copper (Cu) and oxygen (O_2) combine to form two different compounds, demonstrating the Law of Multiple Proportions.

2.17 Electrostatic Potential Energy

In chemical systems, a more important form of potential energy comes from the interaction between two charged particles, such as two electrons or an electron and a proton. In these cases, the potential energy is described by

$$E_p = \frac{q_1 q_2}{4\pi\varepsilon_o r} \qquad (2.6)$$



Here, E_p is the **electrostatic potential energy**, q_1 = charge on particle 1, q_2 = charge on particle 2, e_o = a constant called the vacuum permittivity, r = the distance between the charges q_1 and q_2.

Careful inspection of equation 2.6 reveals three important points:

1) When the two oppositely charged particles (such as one proton and one electron) are infinitely far apart (r, and therefore the denominator, is very large), the electrostatic potential energy goes to zero (E_p = 0). This important result is our arbitrary reference point for potential energy in most chemical systems.

2) We see that as the magnitudes of the charges on the particles increase (in the numerator), the magnitude of the potential energy also increases.

3) Finally, note the implications of the sign of the Coulomb potential energy, depending on what particles are interacting. For two electrons at some fixed distance apart, since both particles are negatively charged, the electrostatic potential energy is a positive value. A positive value for the potential energy implies a repulsive or “energetically unfavorable” interaction. However, if the two particles have opposite charge (for example, one electron and one proton), the electrostatic potential energy has a negative value. A negative value for the potential energy implies an attractive or “energetically favorable” interaction.

4.2 Balancing chemical reaction equations

A chemical equation is **balanced** when it shows equal numbers of atoms of each element on both sides. Remember that this follows from atomic theory since atoms cannot be created nor destroyed. We use coefficients in front of formulae in chemical reactions to denote the relative number of atoms or molecules or moles or formula units involved in the reaction. We do not, however, change the subscripts (chemical formulae themselves) to balance a chemical equation, since that would change the substances. The absence of a coefficient is understood to imply a "1".

Consider the reaction between methane (CH_4) and bromine (Br_2):

$$CH_4(g) + Br_2(l) \rightarrow CBr_4(g) + HBr(l) \quad \text{(unbalanced)}$$

Count:	1 C atom	1 C atom
	4 H atoms	1 H atom
	2 Br atoms	5 Br atoms

As written, this equation is not balanced because it violates the Law of Conservation of Mass. Although one carbon atom is indicated on both the left side and right side of the equation, two bromine atoms (one Br_2 molecule) appear on the left and five bromine atoms appear on the right. Likewise, four hydrogen atoms are shown on the left and one hydrogen atom on the right. The order in which you balance the atoms

does not matter, so count the atoms on each side of the chemical equation and use coefficients to make those values equal. We start by balancing the number of H atoms on each side of the equation. If we put the coefficient 4 in front of hydrogen bromide (HBr) we will have equal numbers of hydrogen atoms on each side of the arrow:

$$CH_4(g) + Br_2(l) \rightarrow CBr_4(g) + 4HBr(l) \text{ (unbalanced)}$$

Count:	1 C atom	1 C atom
	4 H atoms	4 H atom
	2 Br atoms	8 Br atoms

At this point, we have balanced the number of carbon atoms and hydrogen atoms in the equation. But the bromine atoms are not balanced. We can balance the equation by placing a 4 in front of the bromine molecule. Thus,

$$CH_4(g) + 4Br_2(l) \rightarrow CBr_4(g) + \mathbf{4}HBr(l)$$

Count:	1 C atom	1 C atom
	4 H atoms	4 H atom
	8 Br atoms	8 Br atoms

In a more complex example, let's balance the following equation:

$$MoF_6 + Mo(CO)_6 \rightarrow MoF_3 + CO$$

When we inspect this equation we see that none of the 4 types of atoms are balanced.

$$MoF_6 + Mo(CO)_6 \rightarrow MoF_3 + CO \text{ (unbalanced)}$$

Count:		
	6 F atoms	3 F atoms
	6 C atoms	1 C atoms
	2 Mo atoms	1 Mo atom
	6 O atoms	1 O atoms

So we start with an atom that appears in a species only once on each side of the equation, such as fluorine. We can get 6 F atoms on the right by placing a 2 in front of MoF_3

$$MoF_6 + Mo(CO)_6 \rightarrow 2MoF_3 + CO \text{ (unbalanced)}$$

This change balances the Mo on both sides. We now balance C. We have 6 atoms on the left and 1 C on the right. We can balance the C atoms by placing a 6 in front of CO:

$$MoF_6 + Mo(CO)_6 \rightarrow 2MoF_3 + 6CO \text{ (balanced)}$$

In summary, there is no right or wrong way to balance a chemical equation. The following simple steps can be helpful:

1. Write the chemical equation with correct formulas. Do not change these formulas in the course of balancing the equation.
2. Count the number of each type of atom on both sides of the chemical equation.
3. Try different coefficients (whole numbers) in front of each substance to give equal numbers of each atom on both sides of the arrow:
   a) for equations that include a substance that has a more complex formula than the other substances, try to balance the number of atoms in that substance by changing coefficients for the substance(s) that also contain those atom types because changing coefficients for simpler substances affects fewer elements; then finish by changing coefficients for atoms that occur as free elements; or

   b) start changing the coefficient for a substance that appears the fewest times on each side for the chemical equation. Often, this will be a "heavy" atom (non-hydrogen atom).

   c) if a diatomic molecule is a reactant or product, leave that substance to balance last and use a fractional coefficient (such as 3/2, 5/2, etc.) to give the correct number of that type of atom.
4. If you end up with fractional coefficients, multiply the entire equation through by the denominator (usually 2) to get whole number coefficients.

6.7 Wave-particle duality

An important concept in the preceding discussion of the energy of light (and electromagnetic radiation in general) is that light has both particle properties and wave properties. And since light can exhibit both types of properties, electromagnetic radiation is said to have **wave-particle duality**. Wave-particle duality can be a difficult concept to grasp especially since there are no significant examples to cite in the macroscopic world. A simple, non-scientific example from the macroscopic world is the "spork" (Figure 6.12), a utensil that has the tines of a fork (fork-like properties) and the shallow bowl of a spoon (spoon-like properties). Hence a spork can function as either utensil under different circumstances. In science, we have to be careful when drawing conclusions that involve extrapolating outside of the range of measurement, something that is often necessary and useful. In other words, all of direct human experience involves the macroscopic world. Scientists accept the concept of wave-particle duality because it is useful in explaining experimental results even though we cannot directly experience it.

Figure 6.12 Diagram of a "spork"

In 1922, Arthur Compton was investigating the scattering of X-rays by matter and observed that the scattered X-rays

had longer wavelengths than the incident X-rays. He attributed this phenomenon to the transfer of energy from the photon of the X-ray to the electron in the matter as a result of collision. Importantly, a transfer of **momentum** accompanied this transfer of energy from the photon (momentum is a measure of the tendency of an object to continue moving in the direction of its current motion, and is defined by the equation p = mv). Compton was able to calculate the momentum **p** of a photon as

$$p = \frac{h\nu}{c} \qquad (6.7)$$

Compton's experiment provided additional evidence of the particle nature of light because momentum is a property of particles, not a property of waves.

In 1924 Louis de Broglie proposed that matter, like light, has wave-particle duality. He started with Compton's equation for the momentum of a photon and assumed that it applied to moving particles as well. He substituted $1/\lambda$ for ν/c (by rearranging equation 6.1) and replaced p with mv, yielding

$$\mathrm{mv} = \frac{h}{\lambda} \qquad (6.8)$$

Rearranging equation 6.8 to solve for wavelength, de Broglie's equation is obtained:

$$\lambda = \frac{\mathbf{h}}{\mathbf{m}v} \qquad (6.9)$$

Equation 6.9 in which wavelength (of a wave) is related to momentum (of a particle) represents the concept of wave-particle duality; that is, all particles of matter also have wave-like properties. The de Broglie equation says that as the mass or velocity of a particle increases its wavelength decreases. Further, de Broglie asserted that we cannot pretend to measure the microscopic properties of macroscopic systems and that we must learn to accept the fact that whatever electrons and photons are, they have a dual nature. In some experiments, they behave more like particles and in other experiments more like waves.