4.1: The Speed of Reactions

Skills to Develop

- Describe the effects of chemical nature, physical state, temperature, concentration, and catalysis on reaction rates

So far, we have considered many chemical reactions that can occur and described them using chemical equations and stoichiometry. In real situations, however, just as important as knowing whether a reaction can occur is knowing how fast it will occur - and how to control that speed. The speed of a reaction is given by the **reaction rate**, a measure of how fast reactants are consumed and products are formed. The study of reaction rates is known as chemical **kinetics**.

The central theory of kinetics is *collision theory*. The premise of this theory is simple: molecules have to collide to react. Therefore, the speed at which a reaction takes place depends on two main factors:

- The frequency of collisions: The more often molecules collide with each other, the faster the reaction proceeds.
- The energy of collisions: The more forcefully molecules collide with each other, the more likely they are to react, and the faster the reaction proceeds.

The rates at which reactants are consumed and products are formed during chemical reactions vary greatly. We can identify five factors that affect the rates of chemical reactions: the chemical nature of the reacting substances, the physical state of the reactants, the temperature of the reactants, the concentration of the reactants, and the presence of a catalyst.

The Chemical Nature of the Reacting Substances

The rate of a reaction depends on the chemical nature of the participating substances. Reactions that appear similar may have different rates under the same conditions, depending on the identity of the reactants. For example, when small pieces of the metals iron and sodium are exposed to air, the sodium reacts completely with air overnight, whereas the iron is barely affected. The active metals calcium and sodium both react with water to form hydrogen gas and a base. Yet calcium reacts at a moderate rate, whereas sodium reacts so rapidly that the reaction is almost explosive.

The Physical State of the Reactants

Reactions in phases that easily mix, such as gases and liquids, occur much faster than reactions between solids. The extent of mixing of the reactants influences the frequency of molecular collisions - if reactants are more thoroughly mixed, the molecules will collide more often and thus react faster. For this reason, many chemical reactions are carried out in solution, where the reactants can easily move around through the solvent. For the same reason, reactions that are stirred proceed faster than reactions that proceed by diffusion.

Except for substances in the gaseous state or in solution, reactions occur at the boundary, or interface, between two phases. Hence, the rate of a reaction between two phases depends to a great extent on the surface contact between them. This depends on the *state of subdivision* of the reactants. A finely divided solid has more surface area available for reaction than does one large piece of the same substance. Thus a liquid will react more rapidly with a finely divided solid than with a large piece of the same solid. For example, large pieces of iron react slowly with acids; finely divided iron reacts much more rapidly (Figure 4.1.1). Large pieces of wood smolder, smaller pieces burn rapidly, and saw dust burns explosively.

Figure 4.1.1: (a) Iron powder reacts rapidly with dilute hydrochloric acid and produces bubbles of hydrogen gas because the powder has a large total area: $2Fe(s) + 6HCl(aq) \longrightarrow 2FeCl_3(aq) + 3H_2(g)$. (surfaceb) An iron nail reacts more slowly.

***Video* $4.1.1$**: *The reaction of cesium with water in slow motion and a discussion of how the state of reactants and particle size affect reaction rates.*

Temperature of the Reactants

Chemical reactions typically occur faster at higher temperatures. Food can spoil quickly when left on the kitchen counter. However, the lower temperature inside of a refrigerator slows that process so that the same food remains fresh for days. We use a burner or a hot plate in the laboratory to increase the speed of reactions that proceed slowly at ordinary temperatures. In many cases, an increase in temperature of only 10 °C will approximately double the rate of a reaction in a homogeneous system.

Again, the reason goes back to molecular collisions. Temperature corresponds to the average kinetic energy of the molecules. Molecules with greater kinetic energy will collide with each other not only more often, but also with more force, increasing the rate of their reaction.

Concentrations of the Reactants

The rates of many reactions depend on the concentrations of the reactants. Rates usually increase when the concentration of one or more of the reactants increases because molecular collisions become more frequent when more reactant molecules exist in the same space. For example, calcium carbonate ($CaCO_3$) deteriorates as a result of its reaction with the pollutant sulfur dioxide. The rate of this reaction depends on the amount of sulfur dioxide in the air (Figure $4.1.2$). As an acidic oxide, sulfur dioxide combines with water vapor in the air to produce sulfurous acid in the following reaction:

$$SO_{2(g)} + H_2O_{(g)} \longrightarrow H_2SO_{3(aq)} \tag{4.1.1}$$

Calcium carbonate reacts with sulfurous acid as follows:

$$CaCO_{3(s)} + H_2SO_{3(aq)} \longrightarrow CaSO_{3(aq)} + CO_{2(g)} + H_2O_{(l)} \tag{4.1.2}$$

In a polluted atmosphere where the concentration of sulfur dioxide is high, calcium carbonate deteriorates more rapidly than in less polluted air. Similarly, phosphorus burns much more rapidly in an atmosphere of pure oxygen than in air, which is only about 20% oxygen.

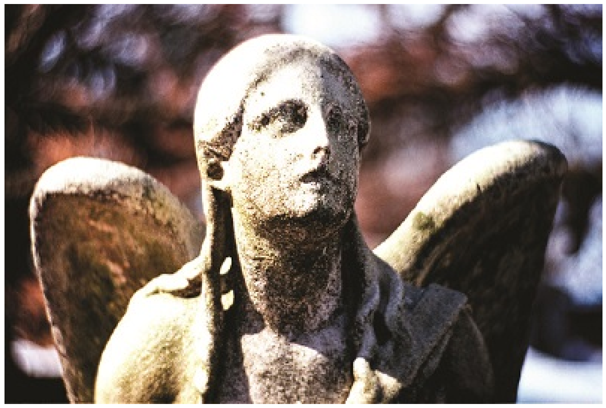

Figure 4.1.2: Statues made from carbonate compounds such as limestone and marble typically weather slowly over time due to the actions of water, and thermal expansion and contraction. However, pollutants like sulfur dioxide can accelerate weathering. As the concentration of air pollutants increases, deterioration of limestone occurs more rapidly. (credit: James P Fisher III).

***Video* 4.1.2**: *Phosphorous burns rapidly in air, but it will burn even more rapidly if the concentration of oxygen in is higher.*

The Presence of a Catalyst

Hydrogen peroxide solutions foam when poured onto an open wound because substances in the exposed tissues act as **catalysts**, increasing the rate of hydrogen peroxide's decomposition. However, in the absence of these catalysts (for example, in the bottle in the medicine cabinet) complete decomposition can take months. A catalyst is a substance that increases the rate of a chemical reaction without itself being consumed by the reaction. A catalyst increases the reaction rate by providing an alternative pathway or mechanism for the reaction to follow. Catalysis will be discussed in greater detail later in this chapter as it relates to mechanisms of reactions.

> *Chemical reactions occur when molecules collide with each other and undergo a chemical transformation. Before physically performing a reaction in a laboratory, scientists can use molecular modeling simulations to predict how the parameters discussed earlier will influence the rate of a reaction. Use the PhET Reactions & Rates interactive to explore how temperature, concentration, and the nature of the reactants affect reaction rates.*

Summary

The rate of a chemical reaction is affected by several parameters. Reactions involving two phases proceed more rapidly when there is greater surface area contact. If temperature or reactant concentration is increased, the rate of a given reaction generally increases as well. A catalyst can increase the rate of a reaction by providing an alternative pathway that causes the activation energy of the reaction to decrease.

Glossary

reaction rate
: the speed at which reactants are consumed and products are formed in a chemical reaction

kinetics
: the study of the rates of chemical reactions

catalyst
: substance that increases the rate of a reaction without itself being consumed by the reaction

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