GENERAL CHEMISTRY

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Therefore,

$$\text{Molality} = \frac{0.150 \text{ mol } C_6H_6}{78.3 \times 10^{-3} \text{ kg } CH_3C_6H_5} = 1.92 \text{ mol } C_6H_6/\text{kg } CH_3C_6H_5$$

EXERCISE Calculate the molality of a solution of toluene in benzene, given that the mole fraction of toluene is 0.150.

[*Answer*: 2.26 *m*]

SOLUBILITY

In this chapter we are focusing on aqueous solutions because they are so important, but many of our remarks apply equally to nonaqueous solutions. In the following discussion, remember that substances which dissolve to give solutions of ions that conduct electricity (e.g., sodium chloride and acetic acid) are called electrolytes (Section 2.7); those giving solutions that do not conduct electricity because the solute remains molecular (e.g., glucose and ethanol) are nonelectrolytes.

11.3 SATURATION AND SOLUBILITY

If we add 20 g of sucrose—cane sugar—to 100 mL of water at room temperature, all the sucrose dissolves. However, if we add 200 g, most dissolves but some does not (Fig. 11.4). When the solvent has dissolved all the solute it can and some undissolved solute remains, the solution is said to be "saturated."

The definition of solubility. If we could follow a single sucrose molecule in a saturated solution, we might find that at some instant it is part of the surface layer of a sucrose crystal (Fig. 11.5). Shortly after, the molecule might be found in solution. Still later, it might be buried more deeply in a crystal, under many layers of molecules that had settled on
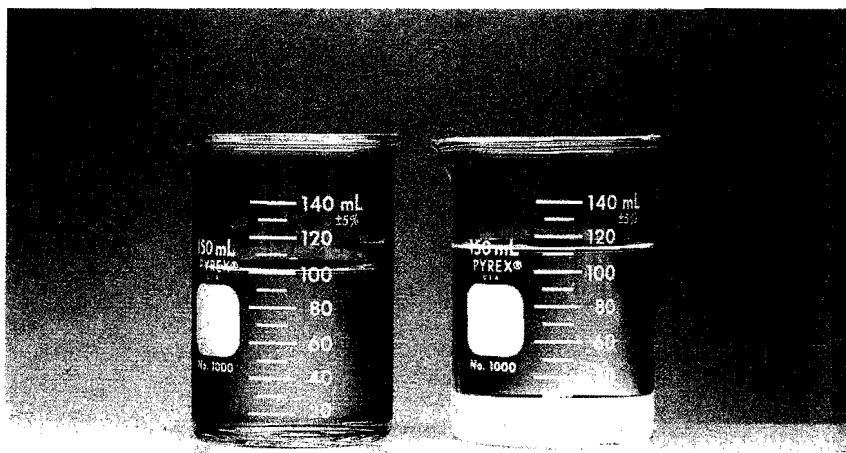

FIGURE 11.4 When a little sucrose is shaken with 100 mL of water, it all dissolves (left). However, when a large amount (more than 200 g) is added, some undissolved sucrose remains (right).

top of it. There it would remain until it became exposed again and was able to return to the solution. In other words, a saturated solution is another example of dynamic equilibrium (see Section 10.4), in which a forward process and its reverse occur at equal rates. In this case, the solute continues to dissolve, and it does so at a rate that exactly matches the rate of the reverse process, the return of solute from the solution. This suggests the following definition:

A **saturated solution** is a solution in which the dissolved and undissolved solute are in dynamic equilibrium.

Although we cannot follow a single molecule in a saturated solution, we can show experimentally that the equilibrium is dynamic and not static. One way to do so is to add solid silver iodide, containing some iodine-131 in place of the usual iodine-127, to a saturated solution of silver iodide. Iodine-131 is radioactive and can be detected with Geiger counters and other radioactivity-detection devices. After a time the solution becomes radioactive, but the total mass of dissolved solid remains unchanged. This shows that some I^- ions have dissolved and others have come out of solution, even though the solution was already saturated.

A saturated solution represents the limit of a solute's ability to dissolve in a given quantity of solvent. It is therefore a natural measure of the solute's "solubility" S:

The **solubility** of a substance in a solvent is the concentration of the saturated solution.

The solubilities of some substances are given in Table 11.3. They depend on the solvent, the temperature, and, for gases, the pressure.

TABLE 11.3 **The solubilities of some substances**

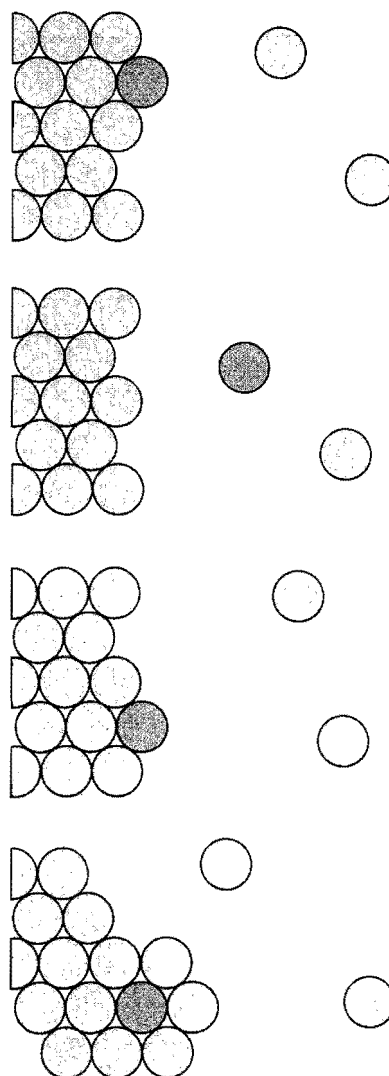| Compound | Solubility, g solute/100 g solvent, in water at | | Other solvents |
	0°C	100°C or as specified	
NH_3	89.5	7.4	Organic solvents
NH_4NO_3	118	871	Alcohol, ammonia
$CaCl_2$	59.5	159	Alcohol
CaF_2	1.7×10^{-3}		
$CuSO_4 \cdot 5H_2O$	31.6	203.3	
HCl	82.3	56.1 at 60°C	Alcohol, benzene
MgO	6×10^{-4}	8×10^{-3} at 30°C	
AgF	182	205	
AgCl	7×10^{-5}	2×10^{-3}	

FIGURE 11.5 The solute in a saturated solution is in dynamic equilibrium with the undissolved solute. If we could follow a single solute particle (the red circle), we would sometimes find it in solution and sometimes in the solute.
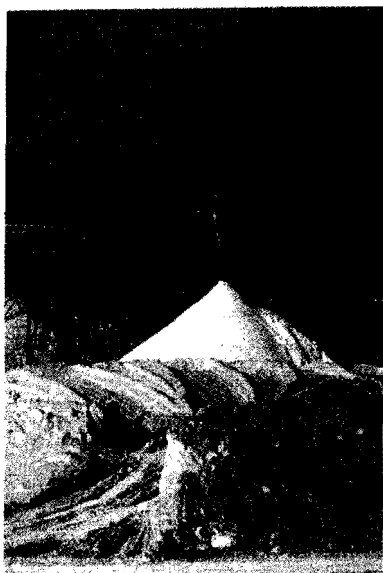
FIGURE 11.6 This Chile saltpeter has survived in the arid region where it is mined in Chile because there is too little groundwater to dissolve it and wash it away.

The dependence of solubility on the solute. Some substances are soluble in water, others sparingly (slightly) soluble, and others almost insoluble. We can know which behavior to expect by referring to the "solubility rules," which were given in Table 3.1. We used the rules in Chapter 3 to choose reagents for precipitation reactions; they are also of help in understanding the behavior of some everyday substances and the properties of minerals. Because of the solubility of most nitrates, for instance, they are rarely found in mineral deposits, for they are usually carried away by the water that trickles through the ground. An exception is the large deposit of sodium nitrate in the arid coastal region of Chile, where groundwater is absent. This "Chile saltpeter" (Fig. 11.6) was the main source of nitrates for fertilizers and explosives until the Haber process for ammonia was developed at the start of this century.

The low solubility of most phosphates is an advantage for skeletons, since bone consists largely of calcium phosphate (much of the rest is the protein collagen). However, this insolubility is inconvenient for agriculture, since it means that phosphorus, which is essential to the function of biological cells, is slow to circulate through the ecosystem. One of chemistry's achievements has been the development of manufacturing processes to speed phosphates on their way as fertilizers. The phosphates and hydrogen phosphates used for fertilizers are obtained from phosphate rocks (Fig. 11.7), principally the apatites—hydroxyapatite, $Ca_5(PO_4)_3OH$, and fluorapatite, $Ca_5(PO_4)_3F$—by treating them with concentrated sulfuric acid:

$$Ca_5(PO_4)_3OH(s) + 5H_2SO_4(aq) \longrightarrow$$
$$3H_3PO_4(aq) + 5CaSO_4(s) + H_2O(l)$$
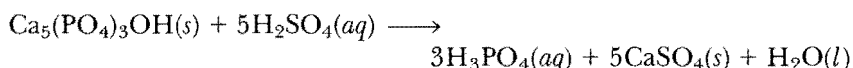
The phosphate rocks themselves were once alive, for they are the crushed and compressed remains of the skeletons of prehistoric animals. Calcium hydrogen phosphate ($CaHPO_4$) is more soluble than calcium phosphate and is included in commercial phosphate fertilizers.

Just as hydrogen phosphates are more soluble than phosphates, so hydrogen carbonates (bicarbonates, HCO_3^-) are more soluble than carbonates. This difference is responsible for the behavior of *hard water*, water that contains dissolved calcium and magnesium salts. In particular, the difference accounts for the deposit of scale inside hot pipes and for the formation of a scum with soap in hard water. The

FIGURE 11.7 Mining of phosphate rock, the crushed remains of the skeletons of prehistoric animals.

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