

7.7: Solubility

Learning Outcomes

- List examples of solutions made from different solute-solvent combinations.
- Distinguish between saturated and unsaturated solutions.
- Explain the effects of temperature on the solubility of solids and gases.
- Use a solubility curve to determine the solubilities of substances at various temperatures.
- Explain the effect of pressure on the solubility of gases.

Previously, we looked at the primary characteristics of a solution and how water is able to dissolve solid solutes. There are many examples of solutions that do not involve water at all, or solutions that involve solutes that are not solids. The table below summarizes the possible combinations of solute-solvent states, along with examples of each.

Table 7.7.1: Solute-Solvent Combinations

Solute State	Solvent State	Example
liquid	gas	water in air
gas	gas	oxygen in nitrogen (gas mixture)
solid	liquid	salt in water
liquid	liquid	alcohol in water
gas	liquid	carbon dioxide in water
solid	solid	zinc in copper (brass alloy)
liquid	solid	mercury in silver and tin (dental amalgam)

Air is a homogeneous mixture of many different gases and, therefore, qualifies as a solution. Solid-solid solutions, such as brass, bronze, and sterling silver, are called alloys. Fish depend on oxygen gas that is dissolved in the water found in oceans, lakes and rivers (see figure below). While solid-liquid and aqueous solutions comprise the majority of solutions encountered in the chemistry laboratory, it is important to be aware of the other possibilities.



Figure 7.7.1: Large aquariums like this salt-water tank have air continually bubbled into the water so that the fish have enough dissolved oxygen to breathe.

Rate of Dissolving

We know that the dissolving of a solid by water depends upon the collisions that occur between the solvent molecules and the particles in the solid crystal. Anything that can be done to increase the frequency of those collisions and/or to give those collisions more energy will increase the rate of dissolving. Imagine that you were trying to dissolve some sugar in a glassful of tea. A packet of granulated sugar would dissolve faster than a cube of sugar. The rate of dissolving would be increased by stirring, or agitating the solution. Finally, the sugar would dissolve faster in hot tea than it would in cold tea.

Surface Area

The rate at which a solute dissolves depends upon the size of the solute particles. Dissolving is a surface phenomenon, since it depends on solvent molecules colliding with the outer surface of the solute. A given quantity of solute dissolves faster when it is ground into small particles than if it is in the form of a large chunk, because more surface area is exposed. The packet of granulated sugar exposes far more surface area to the solvent and dissolves more quickly than the sugar cube.

Agitation of the Solution

Dissolving sugar in water will occur more quickly if the water is stirred. The stirring allows fresh solvent molecules to continually be in contact with the solute. If it is not stirred, then the water right at the surface of the solute becomes saturated with dissolved sugar molecules, meaning that it is more difficult for additional solute to dissolve. The sugar cube would eventually dissolve because random motions of the water molecules would bring enough fresh solvent into contact with the sugar, but the process would take much longer. It is important to realize that neither stirring nor breaking up a solute affect the overall amount of solute that dissolves. It only affects the rate of dissolving.

Temperature

Heating up the solvent gives the molecules more kinetic energy. The more rapid motion means that the solid or liquid solvent molecules collide with the solute with greater frequency, and the collisions occur with more force. Both factors increase the rate at which the solid or liquid solute dissolves. As we will see in the next section, a temperature change not only affects the rate of dissolving, but it also affects the amount of solute that can be dissolved.

Types of Solutions

Table salt (NaCl) readily dissolves in water. Suppose that you have a beaker of water to which you add some salt, stirring until it dissolves. Then you add more, and that dissolves as well. If you keep adding more and more salt, eventually you will reach a point at which no more of the salt will dissolve, no matter how long or how vigorously you stir it. Why? On the molecular level, we know that the action of the water causes the individual ions to break apart from the salt crystal and enter the solution, where they remain hydrated by water molecules. What also happens is that some of the dissolved ions collide back again with the crystal and remain there. **Recrystallization** is the process of dissolved solute returning to the solid state. At some point, the rate at which the solid salt is dissolving becomes equal to the rate at which the dissolved solute is recrystallizing. When that point is reached, the total amount of dissolved salt remains unchanged.

When the solution equilibrium point is reached and no more solute will dissolve, the solution is said to be saturated. A **saturated solution** is a solution that contains the maximum amount of solute that is capable of being dissolved. At 20°C , the maximum amount of NaCl that will dissolve in 100. g of water is 36.0 g. If any more NaCl is added past that point, it will not dissolve because the solution is saturated. What if more water is added to the solution instead? Now, more NaCl would be capable of dissolving, since there is additional solvent present. An **unsaturated solution** is a solution that contains less than the maximum amount of solute that is capable of being dissolved. The figure below illustrates the above process, and shows the distinction between unsaturated and saturated.

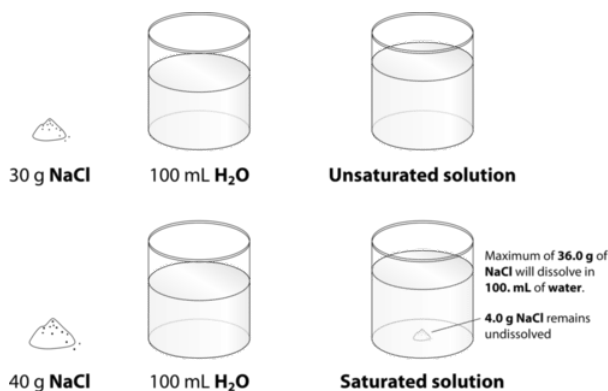


Figure 7.7.2: When 30.0 g of NaCl is added to 100 mL of water at 20°C , it all dissolves, forming an unsaturated solution. When 40.0 g is added, 36.0 g dissolves and 4.0 g remains undissolved, forming a saturated solution.

How can you tell if a solution is saturated or unsaturated? If more solute is added and it does not dissolve, then the original solution was saturated. If the added solute dissolves, then the original solution was unsaturated. A solution that has extra undissolved solute

at the bottom of the container, must be saturated (see figure below).



Figure 7.7.3: A saturated solution of salt (sodium chloride) with undissolved solute remaining at the bottom of the measuring cup.

Solubility Values

The **solubility** of a substance is the amount of that substance that is required to form a saturated solution in a given amount of solvent at a specified temperature. Solubility is often measured in grams of solute per 100 g of solvent. The solubility of sodium chloride in water is 36.0 g per 100 g of water at 20°C. The temperature must be specified because solubility varies with temperature. For gases, the pressure must also be specified. Solubility is specific for a particular solvent. In other words, the solubility of sodium chloride would be different in another solvent. For the purposes of this text, the solubility of a substance will refer to aqueous solubility unless otherwise specified. Solubilities for different solutes have a very wide variation, as can be seen by the data presented in the table below.

Table 7.7.2: Solubility of Solutes at Different Temperatures (g solute in 100 g H₂O)

Substance	0°C	20°C	40°C	60°C	80°C	100°C
AgNO ₃	122	216	311	440	585	733
Ba(OH) ₂	1.67	3.89	8.22	20.94	101.4	—
C ₁₂ H ₂₂ O ₁₁	179	204	238	287	362	487
Ca(OH) ₂	0.189	0.173	0.141	0.121	—	0.07
KCl	28.0	34.2	40.1	45.8	51.3	56.3
KI	128	144	162	176	192	206
KNO ₃	13.9	31.6	61.3	106	167	245
LiCl	69.2	83.5	89.8	98.4	112	128
NaCl	35.7	35.9	36.4	37.1	38.0	39.2
NaNO ₃	73	87.6	102	122	148	180
CO ₂ (1 atm)	0.335	0.169	0.0973	0.058	—	—
O ₂ (1 atm)	0.00694	0.00537	0.00308	0.00227	0.00138	0.00

Factors Affecting Solubility

The solubility of a solid or a liquid solute in a solvent is affected by the temperature, while the solubility of a gaseous solute is affected by both the temperature and the pressure of the gas. We will examine the effects of temperature and pressure separately.

Temperature

The solubility of the majority of solid substances increases as the temperature increases. However, the effect is difficult to predict and varies widely from one solute to another. The temperature dependence of solubility can be visualized with the help of a solubility curve, which is a graph of the solubility vs. temperature. Examine the solubility curves shown (see figure below).

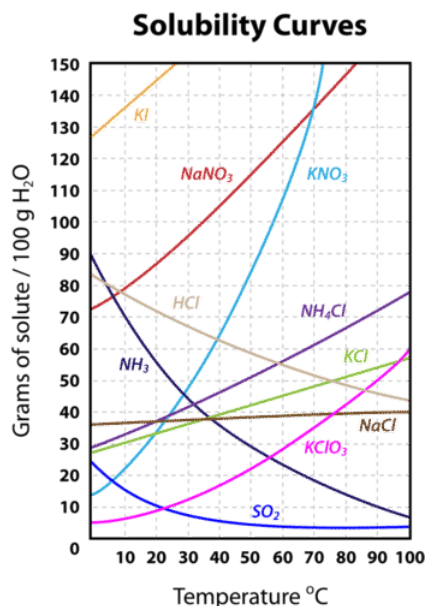


Figure 7.7.4: A solubility curve is a graph of the solubility of a substance as a function of temperature.

Notice how the temperature dependence of NaCl is fairly flat, meaning that an increase in temperature has relatively little effect on the solubility of NaCl. The curve for KNO₃, on the other hand, is very steep; an increase in temperature dramatically increases the solubility of KNO₃.

Several substances listed on the graph - HCl, NH₃, and SO₂ - have solubilities that decrease as the temperature increases. These substances are all gases over the indicated temperature range when at standard pressure. When a solvent with a gas dissolved in it is heated, the kinetic energy of both the solvent and solute increases. As the kinetic energy of the gaseous solute increases, its molecules have a greater tendency to escape the attraction of the solvent molecules and return back to the gas phase. As a result, the solubility of a gas decreases as the temperature increases. This has some profound environmental consequences. Industrial plants situated near bodies of water often use that water as a coolant, returning the warmer water back to the lake or river. This increases the overall temperature of the water, which lowers the quantity of dissolved oxygen, affecting the survival of fish and other organisms.

Solubility curves can be used to determine if a given solution is saturated or unsaturated. Suppose that 80 g of KNO₃ is added to 100 g of water at 30°C. According to the solubility curve, approximately 48 g of KNO₃ will dissolve at 30°C. This means that the solution will be saturated, since 48 g is less than 80 g. We can also determine that there will be $80 - 48 = 32$ g of undissolved KNO₃ remaining at the bottom of the container. Now, suppose that this saturated solution is heated to 60°C. According to the curve, the solubility of KNO₃ at 60°C is about 107 g; the solution is now unsaturated, since it still contains only the original 80 g of solute, all of which is now dissolved. Then, suppose the solution is cooled all the way down to 0°C. The solubility at 0°C is about 14 g, meaning that $80 - 14 = 66$ g of the KNO₃ will recrystallize.

Some solutes, such as sodium acetate, do not recrystallize easily. Suppose an exactly saturated solution of sodium acetate is prepared at 50°C. As it cools back to room temperature, crystals do not immediately appear in the solution, even though the solubility of sodium acetate is lower at room temperature. A **supersaturated solution** is a solution that contains more than the maximum amount of solute that is capable of being dissolved at a given temperature. The recrystallization of the excess dissolved solute in a supersaturated solution can be initiated by the addition of a tiny crystal of solute, called a seed crystal. The seed crystal provides a nucleation site on which the excess dissolved crystals can begin to grow. Recrystallization from a supersaturated solution is typically very fast.

Pressure

Pressure has very little effect on the solubility of solids or liquids, but it has a significant effect on the solubility of gases. Gas solubility increases as the partial pressure of a gas above the liquid increases. Suppose a certain volume of water is in a closed container with the space above it occupied by carbon dioxide gas at standard pressure. Some of the CO₂ molecules come into contact with the surface of the water and dissolve into the liquid. Now suppose that more CO₂ is added to the space above the container, causing a pressure increase. More CO₂ molecules are now in contact with the water, so more of them dissolve. Thus the

solubility increases as the pressure increases. As with a solid, the CO_2 that is undissolved reaches an equilibrium with the dissolved CO_2 , represented by the following equation.



At equilibrium, the rate of gaseous CO_2 dissolving is equal to the rate of dissolved CO_2 coming out of the solution.

When carbonated beverages are packaged, they are done so under high CO_2 pressure so that a large amount of carbon dioxide dissolves in the liquid. When the bottle is opened, equilibrium is disrupted because the CO_2 pressure above the liquid decreases. Immediately, bubbles of CO_2 rapidly exit the solution and escape out of the top of the open bottle. The amount of dissolved CO_2 decreases. If the bottle is left open for an extended period of time, the beverage becomes "flat" as more and more CO_2 comes out of the liquid.

The relationship of gas solubility to pressure is described by Henry's law, named after English chemist William Henry (1774 - 1836). **Henry's law** states that the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas above the liquid.

Supplemental Resources

- Solubility of Things: <http://www.solubilityofthings.com/>
- Solubility Curves: <http://www.kentchemistry.com/links/K...lityCurves.htm>
- Henry's Law: <http://www.kentchemistry.com/links/K.../HenrysLaw.htm>

Contributors and Attributions

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