

Chapter 15: The *Solutions* to All of Your Problems



Urinals, such as the one shown above, are made to collect a solution - pee. This urinal, on the 38th floor of the JR Tower in Hokkaido, is pretty cool looking. In fact, for some reason, the Japanese [generally excel in most things toilet-related](#).

Image: [http://commons.wikimedia.org/wiki/File:JR_Tower_38th_floor_Men%27s_Room_-Hokkaido_\(2008.9.11\).jpg](http://commons.wikimedia.org/wiki/File:JR_Tower_38th_floor_Men%27s_Room_-Hokkaido_(2008.9.11).jpg)

Chapter 15: The *Solutions* to All of Your Problems

All of us are already familiar with solutions. From the Kool Aid we drink to the air we breathe to the flammable liquids used in flamethrowers, solutions are a part of our everyday lives. Let's learn some more about them, shall we?

Spotlight on Science



Figure 15.1: The band Rammstein used flamethrowers utilizing gaseous solutions on stage in 2004. Though their stage show is impressive, Rammstein is mostly known for making nearly unlistenable music.

<http://commons.wikimedia.org/wiki/File:Rammstein-flamethrowers.jpg>

Section 15.1: What's a Solution?

The word **solution** is just another way of saying **homogeneous mixture**. In a solution, one thing (called the **solvent**) dissolves another (called the **solute**), resulting in a mixture with completely uniform composition. If something dissolves in a particular solvent it's said to be **soluble**, and if it doesn't it's said to be **insoluble**. Generally, solutes with similar polarities to the solvent will dissolve much better than solutes with very dissimilar polarities.

Solutions don't always consist of a solid being dissolved in a liquid. Some solutions such as air contain a mixture of gases, while some alloys consist of solids dissolved in other solids.¹

Why does stuff dissolve in the first place?

In the case of aqueous solutions², we find that polar compounds and ionic compounds tend to dissolve much better than nonpolar compounds. The reason for this has to do with the structure of the water molecule (Figure 14.2):

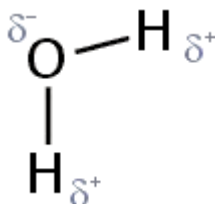


Figure 15.2: The structure of a water molecule. You can see from the δ^+ and the δ^- terms that it's a polar molecule, with partial positive charge on the hydrogen atoms and partial negative charge on the oxygen atom. This polarity is due to the difference in electronegativity between the two elements.

<http://commons.wikimedia.org/wiki/File:Wasser.png>

¹ Not that you asked, but flatulence is a solution containing several gases.

² Solutions in which the solvent is water.

When water molecules come across an ionic compound, the partial negative charge on oxygen is attracted to the cations and the partial positive charges on the hydrogens are attracted to the anions. Because the water molecules are pretty good at pulling the ions off of the crystal, the ionic compound dissolves (Figure 15.3):

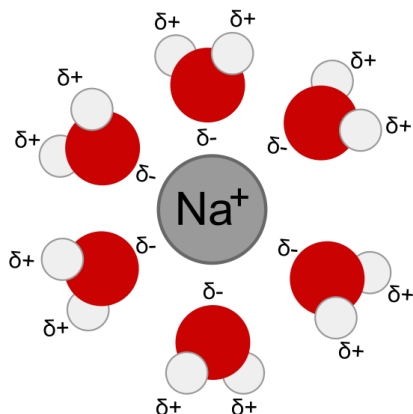


Figure 15.3: When water dissolves sodium chloride, the partial negative charges on oxygen surround the sodium ion, keeping it dissolved in solution. Similarly, the chloride ions are surrounded by the partial positive charges on the hydrogen atoms of water.

<http://commons.wikimedia.org/wiki/File:Na%2BH2O.svg>

Polar compounds dissolve via pretty much the same mechanism, except that it's the attraction between the partial charges of the solute and the partial charges of the solvent that causes it to dissolve.

Nonpolar solutes don't dissolve well in polar solvents because they don't have any partial charges to grab onto. This explains why oil and water don't mix – the oil consists of nonpolar covalent compounds while the water is polar. Likewise, salt doesn't dissolve in gasoline because gasoline is nonpolar and salt is a very polar compound.³

Making Stuff Dissolve Faster

There are several things you can do to make stuff dissolve faster. Let's check them out:

- Shake up the solvent and solute: This causes more of the solvent to come into contact with the solute, making it dissolve more quickly.⁴
- Heat up the solvent and solute: For solutions of solids in liquids, this adds the energy needed to make the solute break apart.⁵
- Grind up the solute: If there are smaller solute particles, then they have a greater surface area and can dissolve more quickly.⁶

³ By definition, ionic compounds have to be polar, since they have a near-complete separation of charge.

⁴ This is why you stir Kool Aid to get the sugar to dissolve more quickly.

⁵ This is why hot tea dissolves sugar faster than cold tea, though there is a solubility aspect to heating as well, which we'll talk about shortly.

⁶ This is why sugar comes as a powder and not as great big crystals.

Solubility

As mentioned a page or so ago, some things dissolve in water and some things don't. Other things dissolve only a little bit. The degree to which a compound dissolves is called its **solubility**.

Some ionic compounds are more likely to dissolve than others. Let's go over some general rules that can tell you whether or not something is soluble in water:

- Acetates and nitrates are soluble, as are compounds containing the ammonium ion.
- Salts containing alkali metals are soluble.
- Bromides are nearly always soluble (exception: AgBr)
- Chlorides are nearly always soluble (exception: AgCl, PbCl₂)
- Silver salts are nearly always insoluble
- For everything else, you need to look at a solubility chart (See [Appendix 3](#))

Talkin' Scientific



Figure 15.4: Solutions are said to be **unsaturated** if more solute can still be dissolved in the solvent (as in salt water), **saturated** if they've dissolved the maximum possible amount of solute (as in overly sugary Kool Aid), and **supersaturated** if they've dissolved more than the quantity that's normally stable. The man to the left is an example of a saturated gravy solution.

http://commons.wikimedia.org/wiki/File:Fat_Joe_in_Portugal.jpg

Variables Affecting Solubility

It turns out that we can change the solubility of a compound by changing some of the parameters under which it exists. Keep in mind that this is different from the section above where we discussed ways to make things dissolve faster – in this section, we're talking about dissolving *more* of something.

- **Increasing the temperature of a solvent generally increases the solubility of solids.** In most cases, the heat needed to break apart a crystal lattice is greater than the energy given off by the solvation process. In this case, increasing the temperature will help to provide more of the energy needed to dissolve the solid.^{7,8}

⁷ This is an application of Le Châtelier's Principle, which we'll learn about when we talk about kinetics.

⁸ There are cases where increasing the temperature of a solvent actually decreases the solubility of a solid solute. These gases occur when the lattice energy is *less* than the energy of solvation. This is true for cerium sulfate, and, at higher temperatures, sodium sulfate.

- **Decreasing the temperature of a solvent generally decreases the solubility of gases.** Because gases have a very high vapor pressure, higher temperatures increase their tendencies to go flying off into the atmosphere. Lowering the temperature of a solvent decreases the available energy for this to occur.
- **Increasing the partial pressure of a gas will cause more of it to dissolve.** Simply put, if more gas molecules hit the solvent, more of them will dissolve. This relationship is shown by Henry's law, which states that the solubility of a gas is directly proportional to its partial pressure:

$$\frac{S_1}{P_1} = \frac{S_2}{P_2}$$

P_1 = initial partial pressure of solute gas
 P_2 = increased partial pressure of solute gas
 S_1 = initial solubility of the gas
 S_2 = solubility of the gas at the higher partial pressure

Spotlight on Important Science Guys



Figure 15.5: William Henry (1774-1836) had awesome hair and mutton chops. In fact, he kind of looks like one of those hipster kids you see hanging around nightclubs (aside from his funny clothes, though a hipster kid might wear them to look "ironic" or some nonsense like that). He died from a self-inflicted gunshot wound.

Plus he made Henry's Law.

http://en.wikipedia.org/wiki/File:William_Henry.jpg

Section 15.2: Numerical Measurements of Concentration

When working with solutions, chemists usually want to know how much solute is dissolved in the solvent (i.e. the concentration). There are a bunch of different ways to do this, so let's check them out:

- **Percent by mass:** The percent by mass is, well, the percent of the weight of the solution that's due to the mass of the solute.⁹ If you like equations, here's how to calculate it:

$$\text{percent by mass} = \frac{\text{mass of solute}}{\text{mass of solution}} \times 100\%$$

⁹ An example: The percent by mass of your head on your body is the percent of your body weight that's due to the mass of your head.

- **Percent by volume:** The percent by volume is the percent of the volume of the solution that's due to the volume of the solute. For example, if you have 15.0 mL of alcohol that has had water added to it until the total volume is 100.0 mL, the percent by volume will be $15.0 \text{ mL} / 100.0 \text{ mL} = 15.0\%$.¹⁰
- **Molarity (M):** Molarity is equal to the number of moles of a solute present in each liter of solution. This is, by far, the most common unit of concentration used by chemists, so my advice is to learn it inside and out. The molarity of a solution is calculated by dividing the moles of solute by the volume of the solution:

$$\text{molarity (M)} = \frac{\text{moles of solute (mol)}}{\text{liters of solution (V)}}$$

- **Molality (m):** The molality of a solution is the number of moles of a solute that has been added to one kilogram of solvent.¹¹

$$\text{molality (m)} = \frac{\text{moles of solute (mol)}}{\text{kg of solvent}}$$

- **Mole fraction (X_n):**¹² The mole fraction of a solute is equal to the number of moles of the solute divided by the total number of moles of all the components in the solution. For example, if you make a solution by adding 2.0 mol of NaCl to 15.0 mol of water, the mole fraction will be equal to $2.0 \text{ mol} / (2.0 \text{ mol} + 15.0 \text{ mol})$. To put this into a more general equation, we find that the mole fraction of compound n in a mixture containing compounds n, o, and p is:

$$X_n = \frac{\text{moles of n}}{\text{moles of n} \times \text{moles of o} \times \text{moles of p}} \dots$$

¹⁰ The reason I made the distinction of adding water to the alcohol until the final volume was 100.0 mL instead of saying "adding 85.0 mL to 15.0 mL of alcohol" is that the volume of a solution is generally slightly less than that of the volume of the solvent and solute added together. It's not a big difference, but significant enough that it should be mentioned.

¹¹ The difference between molarity and molality is this: If you add water to 2.0 moles of a solute until the final volume is 1.0 L, then the molarity is $2.0 \text{ mol} / 1.0 \text{ L} = 2.0 \text{ M}$. If you add 2.0 moles of water to 1.0 L of water (which is equal to one kilogram of water), the molality is $2.0 \text{ mol} / 1.0 \text{ kg} = 2.0 \text{ m}$. The difference is that when you add 2.0 mol of solute to 1.0 kg of solvent, the overall volume of the solution will be greater than 1.0 L. This means that, for aqueous solutions, the molality will always be slightly less than the molarity.

¹² This isn't a letter X, but the uppercase Greek letter *chi*. They look the same, though, so don't worry about it.

Wasting Time by Misusing Important Science Terms



Figure 15.6: Concentration was the name of a TV game show that ran from 1958-1973, from later in 1973 through 1978, and again from 1987-1991. The original host was Hugh Downs (left), who later cohosted the Today show with Barbara Walters. Today had, at one time, featured Florence Henderson, who played Carol Brady on The Brady Bunch, which also starred Robert Reed (Mike Brady) who had earlier costarred on The Defenders, with E.G. Marshall, who was in The Caine Mutiny with Humphrey Bogart, who was really good in that movie.

http://en.wikipedia.org/wiki/File:Hugh_Downs_1972.JPG

Section 15.3: Colligative Properties

When you dissolve stuff into a liquid, the properties of that liquid change. For example, if you add more sugar to Kool Aid, the drink gets stickier and stickier. Any properties of a solution that change when you change the concentration of the solution are called **colligative properties**.

Here are some examples of colligative properties that you might run into:

- **Electrical conductivity:** The more of an electrolyte you dissolve, the higher the electrical conductivity of the solution.¹³ Electrolytes, incidentally, are soluble ionic compounds that create ions when you put them in water. This makes sense – if moving ions is one way that electricity can move around and you place more ions in the solution, the solution will have a greater capacity for moving electricity.
- **The vapor pressure of the solution goes down:** In a pure liquid, all of the molecules at the surface are solute molecules. Because they're all at the surface, they can all evaporate. However, if we add a solute that won't evaporate, some of the surface locations will be filled with these solutes, causing fewer solvent molecules to evaporate and lowering the vapor pressure of the solution.

¹³ If you dissolve non-electrolytes (most covalent compounds) or add insoluble ionic compounds, there is no effect on the electrical conductivity of the solution because there are no additional ions to conduct electricity.

- **The boiling point of the solution goes up:** As you will recall from Chapter 13, a compound boils when its vapor pressure is equal to or greater than the atmospheric pressure.¹⁴ Because adding solute decreases the vapor pressure, higher temperatures are needed to boost the vapor pressure to the atmospheric pressure, causing the compound to boil. There's even an equation to relate the change in boiling point to the concentration of the solution. Here it is:

$$\Delta T_b = K_b m_{\text{eff}}$$

What this equation says is that the increase in boiling point (ΔT) is equal to the ebullioscopic constant of the solvent¹⁵ (0.51°C/m) times the effective molality of the solution. Thus, if we have a 0.75 m aqueous solution of sugar, the change in boiling point will be $(0.51^\circ \text{C/m})(0.75 \text{ m}) = 0.38^\circ \text{C}$. Because this is the increase in water's usual boiling point of 100.00°C , the actual boiling point of the solution will be equal to $100.00^\circ + 0.38^\circ = 100.38^\circ \text{C}$.

Some Stuff about Electrolytes

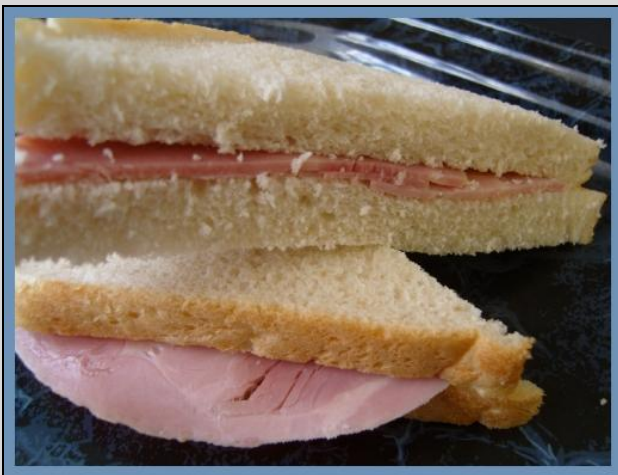


Figure 15.7: When calculation boiling point elevation or freezing point depression, you need to find the effective molality of the solution, which for these compounds is equal to the molality of solute times the number of ions created when it dissolves. For example, CaCl_2 breaks into one Ca^{+2} and two Cl^- ions (for a total of three ions), so a 1.0 m solution of CaCl_2 is actually 3.0 m in total ions. Ham sandwiches, like the one in Figure 17.7, contain electrolytes.

http://commons.wikimedia.org/wiki/File:Ham_sandwich.jpg

- **The freezing point of the solution goes down:** When you've got a pure solvent, the molecules like to line up in nice happy ways so that the intermolecular forces are maximized. However, when you add a solute, these solute particles get in the way of these intermolecular forces, weakening them to the point where it's easier to pull the solvent molecules apart and cause the liquid to melt. The equation that tells us how much the freezing point decreases is:

$$\Delta T_f = K_f m_{\text{eff}}$$

This equation works in exactly the same way as the one for boiling point elevation, except that the constant has a different name (the cryoscopic constant or freezing point depression constant),

¹⁴ For an open beaker, this "atmospheric pressure" actually corresponds to the air pressure in the room. In other environments, it refers to the pressure of whatever gas is in the place where the beaker lies.

¹⁵ Also called the boiling point elevation constant for people who have trouble saying "ebullioscopic."

which for water is 1.86°C/m) and that you subtract the answer from 0.00°C (the usual melting point of water).

- **Osmotic pressure:** You know how a plant gets all wilted when it doesn't have water, and how it gets happy again when you finally throw water into the pot? The reason the plant is able to absorb the water is due to something called **osmosis**, which is when a solvent travels through a membrane to dilute a solute – because the plant cells have stuff dissolved in them¹⁶, the water travels through the cell walls to dilute that stuff. At some point, the pressure of the liquid inside of the cell becomes so high that no more water can travel into it anymore – this is called the “osmotic pressure” of the solution inside the cell. Generally speaking, the osmotic pressure is higher when the concentration of solute is higher, because the water has a stronger tendency to dilute strong solutions than weak ones.

Irrelevant Thing That Has Nothing to do With Osmotic Pressure

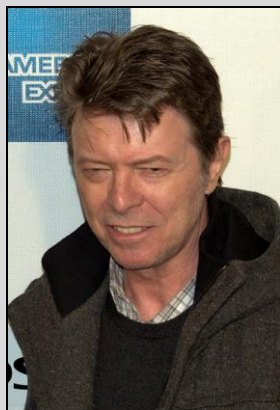


Figure 15.8: David Bowie (seen to the left, looking very old for somebody who used to call himself “Ziggy Stardust”) and Queen recorded a song in 1981 called “Under Pressure”. This song had nothing at all to do with osmotic pressure.

http://commons.wikimedia.org/wiki/File:David_Bowie_at_the_2009_Tribeca_Film_Festival.jpg

Section 15.4: Other Wet Stuff – Colloids and Suspensions

Sometimes, when we put stuff into a solvent, it doesn't dissolve but kind of floats around instead. Unlike solutions (also known as “homogeneous mixtures”), these solutions are heterogeneous because they contain two separate materials that are kind of hanging around in the same place, rather than one having actually dissolved the other. Let's take a look at a few of them:

Suspensions are mixtures in which the suspended component eventually settles to the bottom of the other. One example of a suspension is peanut butter. You know how when you open a jar of peanut butter after it's been closed for a long time and there's a disgusting puddle on top? That puddle is caused by the peanut butter stuff settling to the bottom of the peanut butter suspension. The same thing happens in ketchup, which is why you should shake the bottle up before pouring it to avoid drool from going all over your fries.

¹⁶ I have no idea what – go ask a biology teacher.

Colloids are heterogeneous mixtures where the suspended thing never actually settles. The reason for this is something called “Brownian motion”, which is when the particles are constantly being batted around by the solvent molecules. Think of a bunch of hippies batting a ball around during a concert – because they’re all hitting the ball, it never actually hits the floor.

Scientific Men of Greatness



Figure 15.9: Robert Brown (1773-1858) was the guy who discovered the idea of Brownian motion by looking at pollen under a microscope. Do you think that the man with the last name “Brown” in this picture is Robert Brown? Why or why not?

<http://commons.wikimedia.org/wiki/File:Jamesbrown4.jpg>

There are many different types of colloids, and they’re named depending on the phase of the thing that’s dispersed and the phase of the dispersing medium. Let’s check them out:

- A **sol** is when a solid is suspended in either a solid or liquid. A common sol is paint, where little chunks of colored stuff float around in a solvent.¹⁷
- An **emulsion** is when a liquid is dispersed in either a solid or liquid. My favorite emulsion is milk, because I like to have strong teeth and bones.¹⁸
- A **foam** is when a gas is dissolved in either a solid or liquid. My favorite foam is whipped cream, which I frequently just eat out of the can.¹⁹
- An **aerosol** is when solids or liquids are suspended in a gas. The most disgusting aerosol out there is cigarette smoke, which is a solid suspended in air. Don’t smoke, kids.²⁰

Gases don’t form colloids in other gases, so you don’t need to worry about that.

¹⁷ Actually, paint is both a sol and a solution, because there are chunks of solid floating in a solution of other stuff.

¹⁸ Two things: Milk is both an emulsion and a solution, for the same reason as in #17. Also, I don’t like milk, and was just trying to get you to drink it so you would have good teeth and bones. Though I can’t, for the life of me, figure out why I would possibly care about your teeth or bones.

¹⁹ Which is why I rarely get invited to dinner.

²⁰ Believe it or not, I actually don’t want you to smoke. It’s not that I particularly care about your health – it’s that I don’t feel like smelling your smoke while I’m eating outside at a restaurant. It won’t ruin my meal or anything, but I’d just rather not smell it, because it’s kind of disgusting. Your teeth will look nicer if you don’t smoke, too, which I’ll like because I won’t have to look at your disgusting mouth when I talk to you.

How to tell if something is a solution, suspension, or colloid:

If, for whatever reason, you're curious about whether something is a solution, a suspension, or a colloid, do the following tests on it:

- Let it sit around for a while. If stuff starts collecting on the bottom, it's a suspension.
- Shine a light in it. If you see the beam inside of the mixture, it's a colloid. This tendency to see the beam, called the **Tyndall effect**, is caused by small particles of the dispersed thing reflecting the light you shine through the mixture.²¹
- If it doesn't sink and it doesn't reflect light, it's a solution.

A Lab You Can Do at Home!

If you're interested in solutions, colloids, and suspensions, you can do the tests above to identify common household materials. All you need is 250 mL of the material, a drinking glass, and the ingenuity to perform the tests above. Some household materials that might give interesting results include:

- *Mom's most expensive perfume*
- *That bottle of vodka that dad keeps in the back of the closet for when he's had a hard day.*
- *Juice made from freshly-squeezed peaches.*
- *Your own mucus.*

Really, there's no end to what you can test. Be creative, and have fun!

²¹ Movies make great use of the Tyndall effect. For example, when people are shining a light into a building looking for a bad guy, you can always see the beam of the flashlight because they've pumped smoke into the building to make it look cooler. Likewise with the laser security systems in some movies – normally you can't see laser beams, so they add smoke to make them visible.