Chemistry: Challenges and Solutions
Unit 8: When Chemicals Meet Water
The Properties of Solutions
Hosted by Adam Brunet

[Tease]

A chemical reaction happens when molecules collide. A reaction can take place between molecules that are in the solid state, but two substances can react much more quickly if all the molecules can get at each other at the same time.

This happens when two gases are mixed together. Or two liquids. But it can also happen if solid materials are dissolved in a liquid solvent. And the most common solvent is water.

ETHAN MILLER: We start with our water in our kettle. At a really high temperature you're going to get things that are more soluble and at lower temperatures you are going to be removing things that are less soluble. And at the end of that we are going to get a delicious cup of coffee.

A wide range of compounds can dissolve in water and make what we call aqueous solutions, like the salty ocean.

WHITMAN MILLER: The real problem that we are facing through ocean acidification is that the gas solution from the atmosphere actually mixes with the open ocean, and as it does that, it changes the chemistry of the ocean.

Chemical reactions are the essence of life around us and the majority of them happen in solution.

[Title: Unit 8 – When Chemicals Meet Water]

ADAM BRUNET: What is a solution? You might think of a liquid mixture like gasoline or shampoo, or a sugary sports drink. But solutions do not have to be liquids. They can be solids like the steel frame of a bike, which is a mixture of iron and carbon. Or one of the most important solutions in the world – the air we breathe.

But there's a special place in chemistry for solutions that use water because a majority of solutions that affect us daily, like the blood running through our bodies or the liquid in the vascular system of these trees, all consist of water solutions.

[SEGMENT 1: What is a Solution?]

ADAM BRUNET: Hi, my name's Adam Brunet, and I'm a chemistry professor. I have here the makings of a simple solution. A bottle of H_2O, water, and a powdered sports drink, which is mostly salt and sugar.

Now the water in the bottle is not yet a solution, because it consists of only one kind of molecule: H_2O. But what happens when we add the powder?

The water in this mixture is called the solvent because there is more of it than any of the substances in the powder. The solids in the powder are called solutes. At first, they settle to the bottom of the bottle, so it's not a uniform mixture. If I were to take a taste from the top, I would find that it's very watery. If I were to take a taste from the bottom of the bottle, I would find it to be very sugary and sweet.

After a little while, however, the solids will have dissolved and spread evenly through the water. You don't have to shake it to make it dissolve, but I'm going to speed things up a little.

Now, if I sampled the water anywhere in the container, it has the same amount of dissolved solids throughout, and it would taste the same. We can say that the mixture is homogenous. Now we can call the mixture a solution.

[SEGMENT 2: The Coffee Solution]

ADAM BRUNET: At Dwelltime Café in Cambridge, Massachusetts, one of the most popular solutions on the planet is being prepared daily.

ETHAN MILLER: I became really interested in coffee when I started working at a coffee shop just as a summer job and sort of fell in love with all the intricacies of how it works and how you can change it with really little changes in parameters when you're brewing coffee.

When you roast coffee, the taste changes. When it's very lightly roasted, it's very grassy and a little bit sour. As you roast it a little bit more and more, it becomes a little bit sweeter and a little bit more fruity. And then the darker you get, the more you go into the smoky and bitter.

Before you roast coffee, it's green and hard. It doesn't smell like much. And it's not really soluble. So you need to roast it in order to get out the 900 to 3,000 different solutes. You know, roasted coffee is actually a composite of thousands of different solutes.

When we roast green coffee, we bring it up to about 210 Celsius or maybe around 330 Fahrenheit.

TIMOTHY BORREGO: You're basically cooking this green product and it's going to change it. So in the rotating drum is the green coffee, which is almost not soluble at all. It's going to taste like a terrible cup of coffee if you try to brew it. And in the cooling tray here, you have the roasted coffee, which is going to taste really delicious and aromatic and flavorful – something that you are going to wake up with and get you moving on your day.

ETHAN MILLER: So when we're going to make a cup of coffee, we start with our water and our kettle. And we're going to slowly pour that over our ground coffee. And what's going to happen then is our really hot solvent, is going to combine with our solute, our coffee. And that's going to slowly dissolve all of the 900 to 3,000 different chemical compounds inside of it that give us our brewed coffee. But it's kind of a strange way to think of coffee as dissolving, because you're left with all of these grounds afterwards, and really all you're getting rid of is 1-2% of your coffee.

When people try cold-brew for the first time, a lot of them are really surprised. It doesn't have some of the sourness that a hot coffee might have. It's usually really strong and very chocolaty because of the way we brew it.

TIM BORREGO: I've got about 1000 milliliters of water and 100 grams of coffee, a one to ten ratio. This coarse grind is less soluble compared to a really fine grind. We're using cold water to start off with and we're going to put it in the refrigerator for 24 hours. This is going to differ quite a bit from hot brew in that you can control the extraction versus if you had a hot brew, you're going to extract things very quickly with that high temperature and at lower temperatures over time, you can extract a lot of the really great stuff before you ever reach the point where you're starting to extract some of the more bitter aspects of coffee.

It's got everything in there that you'd want from, you know, a good cup of cold coffee.

ETHAN MILLER: So we have the hot brew coffee, and the cold brew coffee. In the battle of solubility, who will win?

And now we're going to check the TDS of each one, which is the total dissolved solids. We're going to find out what percentage of our solution is made up of solutes. We're going to use a TDS meter and its job is to use an electrical current to tell us how many dissolved solids are in each cup of coffee. We're going to start with the hot brew coffee. Now I'm going to jump right into weighing out the cold brew. I'm going to start by checking the total dissolved solids of the hot brew. And right now we're getting a reading of 735, 736 parts per million. 736 parts per million means that we have a fairly high percentage of our solution is made up of solutes. Now we're going to go into our cold brewed coffee and check the parts per million of solutes in that guy. Looks like this guy has only got 624 parts per million. So it's a much lower percentage of solutes in our solution.

Did temperature play a difference in solubility? Absolutely. The hot brew coffee ended up being way more soluble than the cold brew.

Espresso is a really strong rich cup of coffee that's made with a machine that forces hot water through coffee. The variable that we're going to change when we do an espresso is we're adding a whole lot of pressure to the mix.

So this is a portafilter. This is where the coffee goes when we want to make an espresso. And this guy right here is where all the magic happens.

Ground the coffee nice and fine so we have lots of surface area to work with. It's going to make our coffee really soluble. Now we're going to put the espresso in the big presser. Really force it down with 130 or so psi.

So let's pretend that I'm the water inside an espresso machine. I'm going to get really hot and I'm going to be under a lot of pressure. So when I hit that coffee, I'm going to make things a lot more soluble than I would if we were at one atmosphere of pressure. In that cup, we're going to have this wonderful colloid, which is going to be a suspension of fats and non-dissolved particles as well, so it's going to be really different than just a brewed cup of coffee.

So now we have our finished espresso. As you can see it has this brown, creamy fluid on top, and you can see the solution poking through underneath. And that's an emulsification of fats that have come through, because we've increased the pressure a lot and that's made the fats way more soluble and that's how they ended up in our cup. At nine atmospheres of pressure the fats are really soluble, and now that we have it in this cup at one atmosphere of pressure they're just not very soluble at all, and that's why they all float to the surface.

This is crema, which is just the soluble fats that are inside espresso. Most people think that they're really delicious, but realistically they're just kind of bitter and gross tasting.

Brewing the perfect cup of coffee isn't necessarily an art. It's not really a science either; it's kind of a seamless blend of the two, and we like to think of it more as a craft.

MADISON: Here you go – the perfect latte. Or close to it.

[SEGMENT 3: The Greatest Solvent]

ADAM BRUNET: So, why is water such a great solvent? To answer this question, we need to look at what's going on on the molecular level. I like to look at the example of salt water because it's such a simple and beautiful system.

First we have the H_2O. Now the covalent bonds between the oxygen and the hydrogen are formed by a sharing of electrons between the atomic nuclei. But this sharing is unequal: the oxygen nucleus pulls electrons to itself more strongly than the hydrogen nuclei do. This means that the electrons are a little bit more likely to be found around the oxygen, making it slightly negative, and little bit less likely to be found around the hydrogens, making them slightly positive. Another way of saying this is that the water molecule is a polar molecule: it has a positive end and a negative end.

So now we add the salt. Table salt – NaCl, sodium chloride – is an ionic compound, made up of a positively charged sodium ion and a negatively charged chloride ion. As charged objects are attracted to other charged objects of opposite sign, a polar molecule like water can interact strongly with these ions to help them dissolve. Let's look at how this works in more detail.

When the salt comes in contact with water, the positive sodium ions can become surrounded by the negative oxygen ends of the water molecules. And the negatively charged chloride ions become surrounded by the positive ends of the water molecules. And the separate sodium and chloride ions can then diffuse throughout the entire volume of water, distributing themselves evenly.

When all of the molecules are dispersed in solution, it is the perfect environment for a beautiful reaction to take place.

[SEGMENT 4: DEMO – Solids in Solution]

DANIEL ROSENBERG: Let's see what happens when I try to get two solids to react by mixing. One of them is lead nitrate. The other one is potassium iodide. And when they react, they form a yellow compound.

So let's see what happens when I just mix up the dry powders. There's not much happening there, but why isn't there much happening there? It's like the two big grains of lead nitrate and potassium iodide are bumping against each other, but there's a lot inside and there's not much on the outside, there's not a whole lot of surface area that can react. And so we have to figure out a way that we can give these two solids more surface area to react.

What's the solution? We make a solution. So I'm adding water to the potassium iodide, and as I stir it, these large grains of salt are dissolving in the water. So they're going from a dry chemical to a solution where the potassium iodide is evenly distributed through the entire solution. Now we can make the lead nitrate solution. We're taking a dry powder, and we're dissolving it in water to make a solution of lead nitrate. So, we've gone from a place where we had big pieces of material that could only react on their surfaces to the lead nitrate evenly distributed through the solution, ready to react with every part of the potassium iodide in this solution.

So let's see what happens when we mix them together. But I'm going to do it a little bit at a time. Each time I add, I get a burst of color. Those solutions can react as fast as they can mix. So now, I'm going to pour in the rest, and finish that reaction up. So look how quickly that happened. As quickly as we mixed those two solutions, we got lead iodide precipitating out of this solution, and it's a beautiful yellow color.

In a solution, the molecules are free to move around and interact with each other without regard to surface area. They bump up against each other and they react. And that's why solutions are so powerful in chemistry.

The potassium iodide, KI, and lead nitrate, $Pb(NO_3)_2$, like table salt, are compounds with negatively and positively charged ions that can dissolve in water. Once dissolved, they can recombine in what's called a double displacement reaction.

Lead ions and iodide ions combine to make lead iodide, an insoluble compound that precipitates out of solution as a solid.

The potassium cations and the nitrate anions are left behind still dissolved in the solution. This potassium nitrate that remains is a soluble ionic compound, and the positive and negative ions are stabilized in the solution by the polarity of the water.

[SEGMENT 4: Gases in Solution]

ADAM BRUNET: Most of the solutions we've looked at so far were solids dissolved in an aqueous solution. "Aqueous" just means that the solvent was water. But I'm also very interested in another group of solutions, solutions where the solute is a gas. Understanding that gases can dissolve in water is critical to my ability to dive and return to the surface alive.

[SEGMENT 5: DEMO – The Ammonia Fountain]

DANIEL ROSENBERG: This is the ammonia fountain. This is a fun way of showing that gas can dissolve in water.

In this flask, I have one thousand milliliters of ammonia gas at atmospheric pressure. In order to make this reaction take place, I'm going to add 2mL of water with an indicator that will show us when water and ammonia have mixed to form ammonia water.

Now the ammonia fountain reaction happens the second that I inject this water into this flask. The ammonia gas is going to dissolve into that water entirely, leaving 2mL of ammonia solution, and nothing else in the flask at top.

We'll know it's happening because the water will turn pink. So in the top flask, all of the ammonia has dissolved into this water, and we can see that because the indicator is showing a basic solution. All of this gas in that tiny amount of solution means that up here is a partial vacuum. A partial vacuum connected with a flask full of water and I can open up this stopcock so that the partial vacuum at the top can communicate with the atmospheric pressure water at the bottom. The difference in pressure forces the liquid up into the flask at top. And that is the ammonia fountain.

So what's interesting is that a gas can dissolve in a liquid.

ADAM BRUNET: Understanding how gases dissolve in water is critical to Scuba divers who must be very conscious of decompression sickness, commonly called "the bends." "The bends" is a nitrogen gas solubility problem. The air we breathe is 78% nitrogen, and nitrogen dissolves readily from the lungs into a solution called blood, which is mostly water, and flows through all the tissues of our body.

The amount of nitrogen in your system is affected by the pressure of the air you breathe. As you dive deeper into the ocean, the pressure increases. When the pressure increases the nitrogen becomes more soluble, so there is **more** nitrogen dissolved in your blood, a relationship described by Henry's Law. Henry's Law states that the solubility of a gas in a liquid is proportional to the partial pressure of the gas over the solution.

We say partial pressure because the air a diver breathes from his tank, is a solution of multiple gases and the nitrogen is only a part of the air, so we are talking about the partial pressure due to nitrogen.

So this all becomes an issue that can affect the divers life, because as he moves from the deep water back to the surface, the pressure decreases dramatically and the nitrogen that was soluble in the blood at depth is no longer soluble at the lower surface pressure. The nitrogen then comes out of solution before it reaches the lungs, creating many gas bubbles in the blood that are very painful and can lead to death.

I was swimming around at a relatively shallow depth. The difference in pressure between being about down about 20 feet and being at the surface isn't that much. But as I go deeper, the air I'm breathing is subject to greater and greater pressure from the weight of all that water. And the amount of nitrogen in my blood can reach dangerous levels.

In order to avoid "the bends," I need to take my time coming back to the surface, so that the nitrogen in my blood can escape slowly as I breathe, and my body can adapt to the changing environment.

Understanding how gas is dissolved in a diver's blood is important, but gases don't just dissolve in liquids in a biological solution like blood. They're also important here, where the atmosphere meets the ocean.

[SEGMENT 7: CO_2 in the Water]

At the Smithsonian Environmental Research Center, Whitman Miller and his group are studying the effects of increased atmospheric carbon dioxide on the oceans.

FRITZ REIDEL: Around us we have the atmosphere. It's a solution of gases, composed primarily of nitrogen and oxygen, but also has a large number of trace gases of which carbon dioxide is one of the most important for life and is also a potential hazard and toxin.

WHITMAN MILLER: So many people have heard of global warming through the greenhouse effect, and CO_2 is one of the greenhouse gases that produces that effect.

However, what people don't necessarily know is all of that CO_2 that goes up into the atmosphere doesn't stay there. About a quarter of it actually goes into the world's oceans. And so, the gas solution from the atmosphere actually mixes with the open ocean. And as it does that, it changes the chemistry of the ocean.

FRITZ REIDEL: Simply put, the higher the concentrations of carbon dioxide in the atmosphere, the higher the concentration of carbon dioxide is going to be in the oceans.

WHITMAN MILLER: And since CO_2 functions as an acid in the ocean, the oceans are becoming more acidic.

Miller's team is concerned that the increasing acidity that comes with increased CO_2 levels in the water will have devastating effects on the marine life and ecosystem in the future. Their concern stems from earlier research on the growth of oyster larvae.

WHITMAN MILLER: We did some laboratory-based experiments where we wanted to understand how changing CO_2 concentrations in the water that oyster larvae were grown in, how that affected their growth and how it affected how they make their shells, or what we call the calcification of their shells.

The team found a significant difference between the growth of oysters in pre-industrial CO_2 conditions of 280ppm and in elevated CO_2 conditions of 800ppm, which is what is predicted for 100 years in the future.

WHITMAN MILLER: So what we found was that under high CO_2 conditions, the oysters grew significantly slower, and that they calcified less. So, since we've done the laboratory experiments and knew those were somewhat simplified, we want to know what's happening in the natural environment. And so, the first step to do that is to understand what the natural baseline dynamics of pCO_2 and pH are, in say, the Chesapeake Bay.

But as it turns out, the Chesapeake Bay is a very complex place, and this part of the Chesapeake Bay is also very complicated. And what that means is that we need to sample intensively across time, but also across space, because what is happening here, in this location may be quite different than what's happening just a kilometer away.

While in the open ocean CO_2 levels are fairly consistent, in costal systems where these oysters live the proximity to the land creates wildly fluctuating CO_2 levels.

WHITMAN MILLER: In coastal systems there's an interaction between the land and the sea.

And in this location, we're at an estuarine salt marsh. And so, this salt marsh is actually, it turns out, exporting a lot of CO_2. And that CO_2 actually comes from the growth of these plants through photosynthesis, which is harvesting CO_2 out of the air. When that plant dies, it goes to the ground and begins to decay. And as this decays, the CO_2 is released. And that CO_2 makes its way into these tidal creeks.

And so we want to understand the dynamics in these coastal systems because they're much more complicated than what's going on in the open ocean. And we need to understand what those dynamics are like with respect to night and day, with respect to tidal cycles, with respect to closeness to a salt marsh or an upland forest.

The team sets out to measure the CO_2 levels in the water throughout the day and across a variety of locations. To measure the amount of gas in a liquid, they use a special device, called an equilibrator.

WHITMAN MILLER: So this device is called an equilibrator. Its purpose is to help measure the concentration of CO_2 in that water. So currently, the air in these tubes is at atmosphere. There's a vent straight to the atmosphere. However, when I turn on this valve, it begins pumping water from this creek in. So what happens, as this water comes into these pipes, it mixes with the air space in the equilibrator and, through Henry's Law, the water and the air come into equilibrium. So therefore, if we take a sample of the air, it's reflective of the concentration of CO_2 in the water.

Throughout the Chesapeake Bay, the team has recorded levels of CO_2 varying dramatically from 100ppm to 15,000ppm. Once they understand the baseline dynamics for CO_2 in this area, they can begin experiments to predict how oysters will fare in these conditions in the future, when CO_2 levels are predicted to be even higher.

AMANDA REYNOLDS: So we are going to take juvenile oysters, and we are going to put them in the river so they experience their natural environment. And we're actually going to be adding in extra CO_2, using these bubblers that will be bubbling in CO_2. And so, we're going to take say, the changing CO_2 in the water, what already occurs naturally, which might look like this – up and down, up and down. And we're going to actually elevate that whole graph up a level. So instead of being down here, we're going to elevate it so the change is kicked up a notch. And that way, we can try to predict what might happen to oysters one hundred years from now, when the levels of CO_2 will potentially effect our oyster populations in the Chesapeake Bay.

WHITMAN MILLER: One goal of ours is to try to understand whether CO_2 and pH are important in locating restoration sites, however, understanding the dynamics now and then projecting what may happen in a high CO_2 world may also inform us about where we do restoration efforts in the future.

[WRAP-UP]

ADAM BRUNET: Solutions are all around us. There are gaseous solutions, like the air, aqueous solutions, like the ocean or biological systems, like my blood and there's solid solutions, like the steel alloy. Understanding how they work is critical in understanding the impact that they have on our lives every day.

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