Chemistry: Challenges and Solutions
Unit 10: Acids and Bases
The Voyage of the Proton
Hosted by Adam Brunet

[Tease]

When protons move, a solution can change dramatically.

DANIEL ROSENBERG: Excellent

An acidic solution can dissolve metal, while a carefully balanced solution of acids and bases can have delicious results.

JOANNE CHANG: So in baking, we bake with weak acids and weak bases and when those two react we're left with conjugate acids and conjugate bases. But it's not just a chance encounter. It's putting these ingredients in specific proportions and a lot of times in specific order as well. And that's what leads to a great pastry.

And the food we eat becomes part of our blood that is an amazing reaction zone.

ROBERT STANTON: The body is an amazing compilation of complex interacting reactions that affect each other. If you know the physiology and you know the chemistry of the acid base reactions, you should be able to keep everybody happy and alive in the process.

Acids and bases perform a molecular dance that changes the world by simply moving protons.

[Title: Unit 10 – Acids and Bases]

[SEGMENT 1]

ADAM BRUNET: What is an acid? What is a base? What is the difference between them and why does it matter? We can start to answer some of these questions by looking at the water in this pool. We all know water is H_2O. But there's something going on in this pool that's very interesting and it's worth a second look.

Even in a simple container of pure water, there is molecular activity. A very small portion of this water is deciding not to be H_2O. Occasionally a hydrogen ion or a proton will pull away from the rest of the molecule. When it does, it leaves behind an OH^- ion called hydroxide and a nearby water molecule, H_2O, gains the proton and becomes H_30 with a plus charge, called the hydronium ion. This process is called dissociation.

All acid-based chemistry happens because of the motion of this proton or H^+ ion. The hydronium ion, H_30^+, is a water molecule that has gained a proton, which makes it an acid. It serves as a proton donor because in a reaction it will give up the extra proton. And conversely, the hydroxide ion OH^- is missing a proton relative to water. In a reaction it is a proton acceptor, and therefore it is a base.

At any moment the vast majority of molecules in a sample of water are not dissociated, they remain as H_2O. In fact, in this entire pool, if we could somehow separate out the hydronium and the hydroxide, we would find there is only about 10 mls of the hydronium acid and 10 mls of the hydroxide base. Scattered through this entire pool, that's a very small amount. Because the amounts of acid and base are equal, they cancel each other out and we say that the water is neutral or has a pH of 7. Seven is the mid point of the pH scale. The pH scale runs from zero to 14.

On our scale, zero is the most acidic. It has the greatest concentration of hydronium and the least amount of hydroxide. 14 is the most basic. It has the most hydroxide and the least hydronium.

Now even in an acidic solution, there is still some amount of hydroxide ion, but it gets less and less as we move down the scale. Similarly, in a basic solution there is still some amount of hydronium, but it get smaller and smaller as we move up the scale. Now the tricky part of this scale is that it is logarithmic. If I wanted to make this pool more acidic, I would have to add an acid other than water to it, to increase the number of protons, and thus the concentration of hydronium. How much more than the 10 mls in pure water? 10 times as much. So at a pH of 6, the solution would have to have a 100 mls of hydronium. Now the hydroxide must be 10 times less to remain balanced, so there is only 1 ml of hydroxide to the 100 mls of hydronium. And at a pH of 5, the hydronium concentration goes up 10 times again. Now you have a thousand mls or a a liter of hydronium to a tenth of a ml of hydroxide. By the end of the scale a solution with a pH of zero is extremely acidic. It will have a hundred trillion times more hydronium than hydroxide. A swimming pool with a pH of zero is not one you want to be swimming in. You'll be much happier with a neutral pH of 7.

[SEGMENT 2: DEMO – Corrosive Acids and Bases]

DANIEL ROSENBERG: Today we going to make a strong acid and a strong base and we are going to look at their effects on metal. So our safety gear for today is, safety glasses as usual, gloves because we are working with corrosives, and the lab jacket because my wife gets a little upset if I come home with holes in my clothing.

So hydrochloric acid and sodium hydroxide are our solutions for the day. Hydrochloric acid is formed when hydrogen chloride dissolves in water. And when hydrogen chloride dissolves in water it dissociates completely, forming hydronium ions and chloride ions. Hydronium is acid in water. Sodium hydroxide is a solid and when it dissolves in water, it dissociates completely to form sodium ions and hydroxide ions.

Now in order to visualize the pH of these solutions, I'm going to add universal indicator. In acid, universal indicator is red. In base, the purple color slowly fades to a cornflower blue.

So strong acid, strong base: which is more corrosive? Well that depends on corrosive to what?

I've had students ask me, which would you rather put your finger in? Strong acid or strong base? And I wear gloves because I'm not going to put my finger in either. But if I had to, if you really pressed me, I would put it into the acid because while acid is very corrosive to metals, it's not so much to skin, whereas base will turn your skin into soap. But I'm not going to get any on me. I'm very careful.

But let's look at how these corrosives affect metals. For the acid I'm going to use a piece of magnesium. I put the magnesium into the acid and we see immediately that there is action. Look at those bubbles forming, dissolving in the acid. The hydronium ions are reacting with the magnesium metal, the gas bubbles are hydrogen, and the magnesium is going into solution as magnesium chloride. Look at that go… and it's gone.

So we can see how acid is corrosive, but how are we going to show that this base is corrosive? We're going to use a little piece of aluminum foil in the sodium hydroxide. And we can see that the basic solution is dissolving the aluminum. The aluminum is being oxidized to aluminum hydroxide, and hydrogen gas is evolving: tiny bubbles, tiny corrosive bubbles. So the aluminum is not as reactive a metal, so this is going to take a few minutes.

Okay, that looks like it's all dissolved. So, acid is corrosive and the base is corrosive. Can I add them together to make a super-corrosive that will dissolve both metals? Let's find out.

So we took a corrosive acid and mixed it with a corrosive base and we wound up with a solution where the indicator is green. And that green color tells me that it is a neutral solution. But should we take the indicator's word for it? Let's add the metal and see what happens.

It doesn't look like anything is happening. So we mixed a corrosive acid and a corrosive base to form a neutral solution of salt in water. And salt and water in this case are not going to dissolve the metal. So here we have our whole pH scale: strong acid, pH 0, a strong base, pH 14 and in the middle, pH 7. A corrosive acid and a corrosive base together make a salt solution that is neutral.

ADAM BRUNET: When the acidic solution, rich with positive hydronium ions is added to the basic solution, rich with negative hydroxide, the acids and bases are ready to react. When hydronium and hydroxide come together, they combine to make water. At the same time, the positive sodium ions and negative chloride ions remain behind as an aqueous solution of sodium chloride. When an equal amount of strong acid and strong base react, all that is left is neutral salt water. This process is called neutralization.

[SEGMENT 3: DEMO – A Cheesy Weak Solution]

ADAM BRUNET: Not all acids and bases dissociate completely in water. In fact only the strong ones do. That's why they are called strong acids and bases in the first place. There are relatively few strong acids and bases in the world, only about 20 or so common ones. For example, the hydrochloric acid in my stomach is a strong acid that breaks down the food that I eat.

In contrast, there are many thousands of weak acids and bases in the world. Here we have vinegar, which is a weak acid, and milk, containing proteins that incorporate several weak bases.

Vinegar is a solution of acetic acid in water. It's a weak acid because only a small portion of the acetic acid molecules give up a proton to form hydronium ions. So, in household vinegar, less than one percent of the acetic acids are dissociated, and more than 99% still have the proton attached.

And this milk that I'm heating on the stove here has several soluble proteins that have weakly basic groups on them. Only a small percentage of the weak bases are accepting a proton from the water at any given moment. I'll add a little salt for taste. And now when I add the vinegar to the milk, they begin to react. And with a little heat and some time, we'll see what happens.

The hydrochloric acid in my stomach is a strong acid, meaning 100% of the HCls have given up their protons to make hydronium, which means that at equilibrium none of them are in the form of HCl. In contrast, acetic acid is a weak acid, which means it only partially dissociates in solution. In fact, less than one percent of the molecules have given up their protons to form hydronium and more than 99% retain their proton. The conjugate base is the term we give to the acid once it has given up its proton. In this case, the acetate ion shown here is the conjugate base of acetic acid. Conjugate base just means the acid with a proton missing, and usually a negative charge. At equilibrium, the acetate ion is constantly picking up a proton from the hydronium and the reaction is proceeding this way. At the same time, the acetic acid is giving up a proton to water to make hydronium and the reaction is proceeding this way. That's why we draw the double arrow. The reaction is going both directions at the same time. We call this, dynamic equilibrium. You can essentially think of it as a proton going from one side of the equation to the other.

Now when we combine a weak acid and weak base, they affect each other's equilibrium, shifting to new positions and reaching a pH somewhere between the two solutions we started with.

It turns out that the milk proteins, as the pH falls and they pick up more and more protons, become insoluble in water. And they begin to fall out of solution and clump together. You can see this clearly in the pot. This is cheese, or at least the first phase of cheese.

These gelatinous solids are called the curds. The liquid that drains through is called the whey. They both contain a bit of residual vinegar in them, so to make a proper cheese I would really have to squeeze these curds out. But I'm too impatient to wait so I'm going to try a little right now.

Hmm. Not bad. And because we used a weak acid, acetic acid, instead of something stronger like HCl, I didn't burn my mouth.

[SEGMENT 4: Baked Reactions]

At Flour bakery in Cambridge, Massachusetts, Joanne Chang is combining weak acids and weak bases to make tasty treats.

JOANNE CHANG: I started Flour in September of 2000. We are a bakery-café. We do all of our pastries and all of our cooking and baking in-house.

KEITH BROOKS: I'm a baker. I love weighing ingredients. Yeah baking is a lot of chemistry, a lot of geometry. A little trigonometry.

RACHEL GIBELEY: When you're dealing with bread, it's maybe a little less scientifically perfect. When you're doing a cake, everything has to be just so. My grandmother tries to bake without following a recipe and it, it's always a disaster.

JOHANNA HAMILTON: I have a boyfriend that's a chemist and when we started dating I told him that we had nothing in common and I didn't want to date him and he said, "We have a lot in common. We both do chemistry. Yours just tastes better."

JOANNE CHANG: The things that appeal about baking is that to me it seems a lot more logical. You have a set of ingredients that all react to each other differently, you know depending on the proportion and depending on what you do to them and the temperature and all sorts of inputs. And you put them all together in various ways and then you come up with a quote, "solution," which is you know hopefully a successful cake or pie or whatever. So I feel like there's a lot of parallels between math and science and baking.

Okay so we're going to be making a cake. We're actually making our devil's food cake, which is the base for our midnight chocolate cake. This cake is really interesting because there's a lot of ingredients in it that all react in various ways. So let's start from the top. First we have butter. The second ingredient we have is brown sugar. Eggs and egg yolks. We have the chocolate part of the devil's food cake. We have crème fraîche. And then for dry ingredients, we have cake flour. Then we have kosher salt. This is just for a little bit of flavor. And then finally we have a little bit of baking soda.

We have a lot of acids and a base that are all going to react together and create a really nice, light, fluffy cake. So for acids, first I have crème fraîche. It is heavy cream and buttermilk that have been left out overnight to ferment. Surprisingly, to some people, brown sugar is also an acid. Now white sugar is not acidic. But in order to make brown sugar, what you do is you combine white sugar with molasses and molasses is an acid.

Reacting with all of these acids is our base. This is the baking soda. Now remember, none of these actually come into play as acids and bases until they are wet. That's when the reactions will occur.

So let's get started. I'm going to actually mix my dry ingredients together. I have the cake flour, salt, and baking soda. So you want to evenly distribute it. So I'm mixing together almost all the acids. I have a little bit of acid in with the brown sugar and then the rest of the acids are all together here with the cocoa and the chocolate and the crème fraîche. And then I have my base here with the dry. So here I have my proton donators and here I have my proton accepters and we're going to mix them all together.

So now we have in our batter, the acid and the base are both obviously wet. And so they're starting to react. So when I have a weak acid and a weak base and I combine them together, one of the byproducts is carbon dioxide. And so carbon dioxide comes out in little bubbles and that's all happening right now, but we're actually going to speed this up by putting this in the oven.

I have two different cakes here. I made one with the baking soda. And then, this cake is actually the exact same cake but made without the baking soda. So this one has the acid, but it has no base. So here's my two cakes. One with baking soda and one without and you can really see the difference between the two. I'm going to cut this cake into thirds. It has no baking soda so we can see what it looks like inside. And you can see that it's really dense. It's going to be like really gummy and really chewy, but there's absolutely no chemical reactions going on in here because there's no base. We have no baking soda. So this one, you can see how lightly textured it is, so many bubbles that are in here. Here's a little bit of bigger bubble. There's a million little mini bubbles in here.

So acids and bases together gave us a really nice cake and they definitely lead to a really nice, light, fluffy cake. And then eating it, you actually also realize that some of the acid is left over. Not all of it ends up being used to react with the baking soda and then that actually adds a lot to the flavor of the cake.

Mmmm acids and bases.

[SEGMENT 5: Acidic Pond]

ADAM BRUNET: Weak acids and bases are important in a natural setting like this pond here in Southern Vermont. This is called Little Pond and in the 1950s it was a great place for trout fishing. Now it has a pH of 5. Ponds and lakes should normally have a pH between 6 to 8, so that's very acidic. And it's not a great place to live if you are a fish or a frog. In fact this pond has seen most of its fish and amphibian population die off. So what happened to damage this pond? Acid rain.

Clean rainwater actually is slightly acidic, with a pH a little below 6. This natural acidity comes from the carbon dioxide in the atmosphere, which dissolves in the rainwater and combines with it to form carbonic acid.

The burning of fossil fuels has the unfortunate side effect of adding sulfur and nitrogen oxides to the atmosphere. These compounds combine with water vapor in the air to form sulfuric acid and nitric acid, then get picked up by raindrops and fall to Earth. That's what's causing the rainwater to have such an unnaturally low pH, or high acidity. The rain collects in ponds like this. When the ponds become too acidic, fish and other organisms can't survive.

It may seem strange, but in a dead lake, the water can sometimes be perfectly clear. This is because the natural algae and microorganisms that used to live here and make it murky are gone.

Usually the environment contains some natural bases that can neutralize these acids, such as limestone rocks that contain carbonates of calcium and magnesium.

So let me show you what happens when it rains. I have here a piece of limestone and a solution of dilute sulfuric acid, which is very similar to acid rain. I start by measuring the pH of the acid. It's dilute acid so I don't have to worry if it touches me. And I find that the pH is about 4, similar to that of acid rain. When I run the acid over the limestone, I see what happens when acid rain combines with limestone rocks in nature. Put the pH paper in, and as you can see, the limestone reacting with the acid has neutralized it to where the pH is between 7 and 8, a healthy range for a pond like this one.

Acid rain isn't very concentrated, but I can see the same reaction a little more dramatically by using concentrated sulfuric acid. You can actually see the limestone reacting with the acid as it neutralizes it. Now, not every place has limestone and even where it is found, as acid rain continues to fall, these natural bases can be overwhelmed or run out. Similar processes are at work in your body. Your body tissues are buffered within an even narrower pH range that must be maintained to keep your cells alive.

[SEGMENT 6: DEMO – Buffered Lemonade]

DANIEL ROSENBERG: I'm 60% water, and this is 100% water. The green color of these solutions tells me that they're neutral, around pH 7. Inside of me is also neutral, around pH 7.4. But what happens when I give 100% water a drink of lemonade? Let's find out.

Lemonade is acidic, full of citric acid. Just a teeny little drink of lemonade. Oooh. Ooh that's not good. Oh that's terribly bad. Distilled water had a drink of lemonade and its pH went from 7 to 5. If my pH went from 7 to 5, that would be lethal. So how come I can drink lemonade and still stay alive? It's because inside of me is a collection of weak acids and weak bases that act as a buffer. What's a buffer? Let's make one and find out.

We're going to add equal amounts of weak acid, acetic acid or vinegar, and ammonia, a weak base. The green color tells us that this solution is neutral again, pH 7, pH 7, just like inside my body. But this one's a buffer and this one's not. What does it mean that this is a buffer? Let's see what happens when I give the buffer a little drink of lemonade? Mmm, delicious and no change in pH. What happens if I give the distilled water a drink of lemonade? It's orange. That means its pH is 5. But the buffer did not change in pH very much at all. Why is that? When I add a strong acid or a strong base to a solution, they dissociate 100% into hydronium or hydroxide ions. When I add a weak acid or a weak base to the solution, only about 1% of it dissociates. 99% of the weak acid and the weak base is still left in the solution, ready to neutralize any additional acid or base that I add. So if I add a little bit of acid to this solution, the weak base is dissociating. 98%, 97%, 96, so eventually I'm going to overwhelm the buffer solution and its pH is going to change. Let's see if we can overwhelm this buffer with lemonade.

There we go. So I've overwhelmed this buffer. Inside of me is also a buffer, which is good because I enjoy drinking lemonade. But it's not unlimited. If I were to drink 5 gallons of lemonade, it would probably be lethal. It's a good thing I don't enjoy lemonade that much.

[SEGMENT 7: Removing Acids from the Body]

ADAM BRUNET: Dr. Robert Stanton is the chief of the kidney and hypertension section of the Joslin Diabetes center in Boston, Massachusetts. His work requires a robust understanding of the acid-base chemistry occurring in the human body.

ROBERT STANTON: There's a great deal of chemistry going on in the human body. There are a number of processes that produce acids primarily and there are a number of bases that interact with the acids to keep the overall concentration of acid at a normal level. If there was not a way to get rid of the acid, the proton concentrations inside the cells and inside the body would get to a level at which you would die. The total amount of acid produced by the body on an average day is about 30 thousand millimoles of acid and most of that is what called volatile acid. That means it's a gas. And the gas that's produced is CO_2.

ADAM BRUNET: The huge amount of carbon dioxide produced in your body has to be moved to the lungs to be expelled. Gases in the tissues can be very dangerous, so the body dissolves the CO_2 and combines it with water to make carbonic acid, which partially dissociates into hydronium and bicarbonate. Because the blood is a buffered solution of many weak acids and bases, the extra protons can be transported to the lungs without changing the pH of the blood. When the blood reaches the lungs, the volatile acid, carbon dioxide, comes out of solution and is expelled and the buffered blood circulates through the body, repeating the task.

ROBERT STANTON: That gets rid of the volatile acid. The acid that comes from your diet is called fixed acid because it's not CO_2 that's produced. It's either phosphates, sulfates, or other types of acids that can't be breathed off and the kidney is the one that takes care of that. The main buffer inside the kidney is ammonia, which is NH_3, which is a volatile gas. And the ammonia combined protons and when they're producing NH_4^+ and then you can urinate that out and get rid of the free protons.

ADAM BRUNET: The kidneys and blood both buffer acids and regulate pH, but their buffering capacity has a limit. Diabetic patients create excessive amounts of acid when their bodies can't get enough energy from glucose.

ROBERT STANTON: Ketoacidosis occurs when the cells in the body cannot take up glucose efficiently. The cells look for energy from other sources and the primary other sources are fats and amino acids. And when they break down fats and amino acids, the products that are produced are these ketoacid molecules that produce a large amount of acid associated with them. These can be used for energy sources. But there's a large amount of fixed acid that has to be gotten rid of from the body.

So when somebody comes into the emergency room in ketoacidosis, the pH may be anywhere from 6.8 to 7.2. The acid level in the blood builds up very quickly and often overwhelms the buffer systems that are available to it at the time. Unless you turn off this metabolic process, you can build up enough ketoacids that basically will lead to your death. We give insulin to lower the glucose concentrations and when we give insulin, the cells will start taking the glucose back up and the cells that use the glucose, which is normal metabolism, can stop producing ketoacids. Then after that normal process starts up again, the ketoacids can be converted back to bicarbonate and we restore the pH levels back to normal. So it's actually a fairly straightforward thing to treat as long as you understand the chemistry of the situation and the complex interactions of these processes.

[WRAP-UP]

Understanding acids and bases is critical to fundamental chemistry, to the natural environment, and to how our bodies function. By understanding how acid rain has harmed this lake, we can address the problem. The pollutants that cause acid rain have been greatly reduced in recent years. And ponds like this are in recovery.

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