Acid-Base Reactions in Solution: Crash Course Chemistry #8

Crash Course: Chemistry
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=====Chemistry Can Cause Death (00:00)=====

Alright, so you're studying Chemistry, what's the worse that could happen? In most classes, the worst that can happen is just abject, total failure. You're just like failing the test, failing the class, having to rethink your life choices, maybe even quit, drop out of school, get a job at a diner, and start smoking Lucky Strikes. But in Chemistry, the worst thing that can happen is death. And I don't want to make light of this; labs are dangerous places. Chemists die younger than the average person, both because of workplace accidents and cancer caused by exposure to chemicals. But chemists have also done more to increase the average lifespan of humans on earth than, in my opinion, any other profession. So, it's a necessary hazard.

Last week we talked about stuff mixing together, and that's important for sure. But today and for the next few weeks, we're gonna talk about the actual reactions happening in those solutions, dangerous reactions: atoms reorganizing themselves to create whole new substances. These are the processes that make our world the world that we know and love. Some of them are benign and beautiful, some of them are face-meltingly terrifying, and that's not hyperbole, I mean actual melted faces.

(Intro)

Captain John Mullen, there, he blazed the first wagon trail across the Rocky Mountains into the interior Pacific Northwest. The Captain's only been standing in this spot right here for about seventy-five years. And look what's happened to his face. I know this maybe isn't the face melting you were expecting, but we're not so gruesome here at Crash Course Chemistry. The sorry state of Mr. Mullen's face here is the result of an acid-base reaction, one of the three major types of reactions that happen in solution, that we'll be talking about here at Crash Course Chemistry. And the acid that did this, [points behind him again] was mostly sulfuric acid. Now you may be wondering, who's been coming by and throwing sulfuric acid on statues? Well actually, what's been doing the throwing is clouds, the sky, though the actual source of the sulfuric acid, that's 400 miles away at the Colstrip Power Plant in Colstrip, Montana, and also at coal fired power plants all over the United States.

The United States of America burns about a billion tons of coal per year, and most of that coal, is mined right here in the U.S. Montana, where I live, is home to the Powder River Basin, a geographical location responsible for 40% of America's coal output. Between fifty and seventy freight trains ship out of the Powder River Basin every day. Each train has at least 115 coal cars and is more than a mile and a half long. And all of this coal burning, it has effects, significant effects, acidic effects.

=====Acids and Bases are Complicated (02:25)=====
But first, like, what exactly are acids and bases. Well acids - uh -(Bites lemon) Sour. So sour, that's the first thing that we learned about acids, actually, and that's why acid - ugh - actually means sour in Greek or Latin. Latin. And acids are excellent at dissolving stuff; they kill things and melt your face. What about bases? You might have some idea about what a base is: bitter tasting, slippery like soap; soap is in fact a base. And bases, like acids, are totally dangerous and can melt off your face. They're also like the anti-acid basically. In fact, they're in antacids. If you mix acids and bases together they neutralize each other. But as with most things in chemistry and in life when it comes right down to trying to define exactly what something is, it gets weird and messy and confusing and terrible. So, forget everything you ever learned about acids, wipe the slate clean, the most common acid on earth is water. Wuh? And water is the most common base, and am I saying this purely to confuse you? Yes! Well, mostly to convince you that the world is way more complicated than you thought it was.

In 1923, two guys simultaneously defined acids and bases in the exact same way. Brønsted and Lowry defined them; they didn't classify them by how they acted or what they tasted like or even what they were made of, they defined them. And this was an impressive feat because a huge class of molecules, to some extent or another, act as acids and bases. So to come up with a definition that fit all of them, that was not so simple. Brønsted and Lowry defined an acid as being anything that donates a proton and a base as being anything that accepts a proton. And when we say proton, what we're talking about here is a hydrogen atom without its electron. Usually this is happening in water, acids and bases can react in gas, but almost always they're in an aqueous solution, and when a proton gets donated in water, it is accepted by water. And H_2O is converted into H_3O^+, the hydronium ion. So when an acid is added to water, it dissociates, like any other ionic compound, forming H_3O^+ and a negative ion. The acid has donated a proton to the water. Also a little chemistry terminology thing, we usually just write H^+ or say "protons in solution" when in fact we are referring to hydronium ions. It's just a short hand. In reality, H^+ in aqueous solution is always H_3O^+.

=====Conjugate Acids (04:48)=====

Let's take a look at the dissociation of hydrochloric acid for some more terminology bits here. You see right off the bat that the HCl is donating a proton. With many acids, particularly weaker acids, the reaction can actually go back the other way, with H_3O^+ donating it's proton. So in this situation, every chemical in the reaction, also sometimes the major species, can be called an acid or a base. On the left hand side, the water is accepting the proton so it's the base, and HCl is donating it, so it's the acid. And on the left hand side, the Cl^- would be accepting the proton, so that would be the conjugate base, and the hydronium ion is the conjugate acid. The phrase conjugate acid always used to confuse me because I thought it had something to do with conjugating verbs. But it's actually the older, original sense of the word: the one where conjugal, or marriage related visits for prisoners, come from, which means joined together.

=====Conjugate Bases (05:37)=====

For every acid, there is a conjugate base and for every base there is a conjugate acid.

Previous definitions of acids and bases, particularly the one proposed by our old friend Arrhenius, relied on specific major species. Most notably our friend the OH or hydroxide ion. And while hydroxide is in most bases, it's not in all of them. For example, ammonia acts as a base when it reacts with hydrochloric acid to form ammonium chloride. There's no hydroxide but there is definitely proton donation and acceptance going on.

Now acids and bases are not all created equal. Certain acids really like to get rid of their protons and will only reluctantly convert back to their conjugate base by accepting a proton. We call them strong acids, and the conjugate base is a weak base. The same can be said for strong bases and their weak conjugate acids. The reason why all of the most interesting acid-base chemistry happens in water is that dihydrogen oxide is really great at being either a base, accepting a proton from an acid, or an acid, donating a proton to a base. Thus water is the world's most common acid and also the most common base.

=====Acid-Base Stoichiometry (06:44)=====
So, what does any of this have to do with power plants and John

Mullen's face? When coal is burned the sulfur in it reacts with oxygen to form sulfur dioxide. That sulfur dioxide then reacts with water and oxygen in the air to form sulfuric acid. When that sulfuric acid rains down, a set of acid-base reactions take place that damages limestone and metal, and acidifies the water supply, making life harder for fish, coral, salamanders, and pretty much everything else.

Limestone is mostly made of a chemical called calcium carbonate. The carbonate acts as the base, accepting sulfuric acid's protons and converting them to carbonic acid: the conjugate acid, which breaks down into CO_2 and water. Calcium and sulfate ions may precipitate as a salt that's more commonly known as gypsum. Okay, so the average ton of coal in America is about 3% sulfur. Supposing a hundred percent of those 30 kilograms of sulfur leaves the smoke stack and converts to sulfuric acid, how much limestone could that completely wash away. As I've said before, just follow the units. 30 kilograms of sulfur multiplied by 1000 grams per kilogram, multiply that by 1 mole over 32.1 grams of sulfur to get 935 moles of sulfur in every ton of coal burnt. Now, if every mole of that sulfur is converted to H_2SO_4 and every mole of that sulfuric acid reacts with a mole of limestone converting it to a mole of gypsum, then that's 935 moles of limestone dissolved. There are 100.1 grams of calcium carbonate per mole; if we multiply that by 935 moles we get 93,600 grams or 93.6 kilograms. So each ton of coal burnt by a U.S. power plant produces enough sulfuric acid to dissolve about 94 kilograms of limestone. And as we burn about a billion tons of coal per year, it's safe to say that no statue is safe, except for ones built of materials immune to acids, particularly oxidized copper, which will last pretty much forever. Hence, Lady Liberty's hand presiding over the Planet of the Apes.

So, this is clearly a problem. I mean not just for statues, but acid rain has killed or harmed huge swaths of forests. At the peak of acid rain problems in the U.S. the highest recorded acidity was around that of lemon juice, which I can tell you, is pretty acidic: high enough to irritate human skin.

This first became an issue for the power generation when the British House of Lords, in 1929, ruled that a power station was liable to damages caused to nearby crops by acid rain. So something had to be done, but what? Well, we already know one very common chemical that reacts easily with sulfuric acid: good old limestone, and in England, there is lots of limestone. By passing the smoke stack gases through a limestone slurry the SO_2 converts to an acid and then reacts with the limestone forming $CaSO_3$, calcium sulfate.

Now we're gonna do something a little different for those of you who want to go the extra mile. Assuming that one billion metric tons of 3% sulfur coal was burnt in America every year, and all of it is converted to SO_2, how many tons of limestone would we need to scrub out 100% of that sulfur. Answer us down below in the comments.

The limestone scrubber is a good system, but it's not perfect. Many other flue gas desulfurization systems have been developed, and now through a combination of good policy, good science, and hard work, about 95% of sulfur produced in coal fired power plants in the U.S. is removed before it leaves the smoke stack. And through some even smarter chemistry, some of that SO_2 is actually converted to industrially useful chemicals. For example, pure sulfuric acid, which is used in paper mills, iron and steel making, industrial cleaner, and chemical synthesis. Chemistry! Causing problems but also fixing them.

=====Summary (10:26)=====

Thank you for watching this episode of Crash Course Chemistry. If you were paying attention, you may have learned that Chemistry can cause death, that acids and bases are more complicated than you thought they were, and that acid donates protons while a base accepts them. You also should have learned that when an acid donates a proton it forms a conjugate base and when a base donates a proton it forms a conjugate acid. Also, we did a little bit of acid-base stoichiometry.

=====Credits (10:48)=====

This episode of Crash Course Chemistry was written by Kim Krieger and myself. The script was edited by Blake de Pastino, and our chemistry consultant is Dr. Heiko Langner. Our director, cinematographer, and editor is Nicholas Jenkins. Script supervisor is Caitlin Hofmeister. Sound design is by Michael Aranda, and our graphics team is Thought Café.