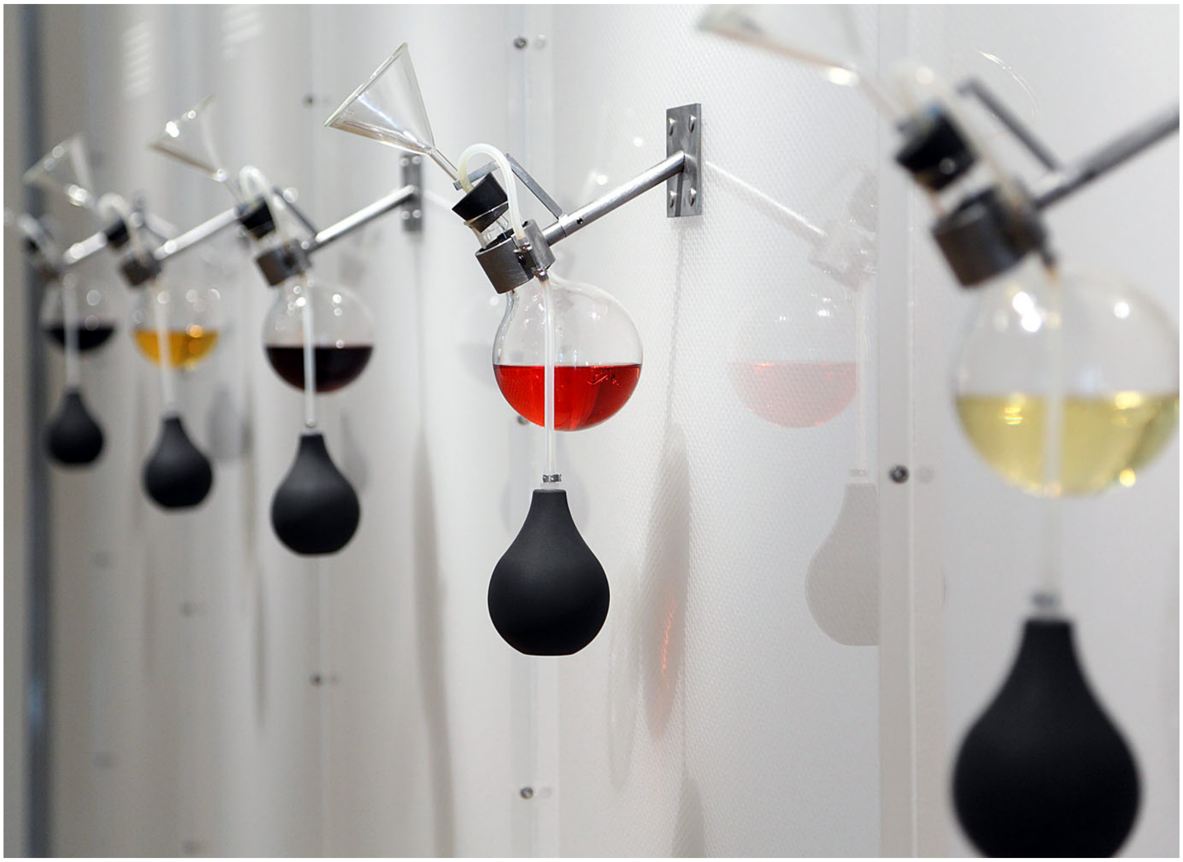
Chemistry



Acids and Bases

by **David Morgan-Mar**

In high school, chemistry was my least favourite science subject. Physics was cool, because it was about how things moved and bounced and crashed, and this included planets and stars and stuff. Biology was fun because it was about animals and plants and how they interacted, and that was always an endless source of fascination. And geology was about the Earth and oceans and mountains and, most importantly, volcanoes, which were about the coolest thing I could imagine apart from planets.[1] Chemistry seemed mostly to be about washing glassware, and those little test tubes you get in high school are darn near impossible to wash properly.

Do chemistry - this might happen!

Chemistry involved Bunsen burners and heating things up, which always, according to my teacher, carried the risk of doing it wrong and splashing hot acid or whatever it was all over your face. You could mix things wrong, or measure them wrong, and your experiment wouldn't work. And reactions generated weird gases that could kill you if you inhaled them, so you had to use fume cupboards to avoid dying right there and then in your science classroom. Chemistry was a dangerous, inexact, difficult, mess that didn't work half the time. And the theory side of it was the dull balancing of reaction equations, which would have been trivially simple algebra if not for the seemingly completely arbitrary additional rules concerning valences that were apparently added for no other reason than to make it harder.

Volcanoes. Much safer.

Looking further back, it was odd how it came to this, since when I was even younger, science essentially was chemistry to me. I was keen on science and that meant having a "chemical set". To do science you had to mix differently coloured things together and see what happened. My parents obliged by buying some little jars of chemicals, some test tubes, and I think a conical flask because that looked cooler than test tubes. There were a few suggested "experiments" in which something mildly interesting happened like the things changing colour or some bubbles being produced, but "real" science was mixing chemicals at random and seeing what happened. Unfortunately what happened pretty much every time was nothing but a greyish sludge in the bottom of the test tube that was impossible to clean out.

Those mysterious numbers.

It was somewhere in between this and high school that chemistry lost its lustre and planets became the coolest thing ever. Perhaps it was fortunate I didn't get to play with real planets, since the mystery and unattainability of actually visiting another planet kept them alive in my mind like some sort of forbidden fruit. Thinking about it now, I guess *Star Wars* didn't hurt either.

It wasn't until I got to university that I started to appreciate chemistry again. The reason, I think, is because that up until then chemistry seems to be more or less arbitrary rules that you just have to know. To understand why those rules exist, you have to dig deeper than high school science allows. You need to appreciate some of the intricacies of quantum mechanics, which dictates things like the numbers of electrons in the shells of atoms.[2] I should say that I skipped HSC chemistry (what some readers might think of as senior high school, or A level chemistry) because I disliked it that much, so probably some of that stuff was taught then. Imagine my horror when I got to university and discovered that for the degree I'd chosen, a year of chemistry was mandatory.

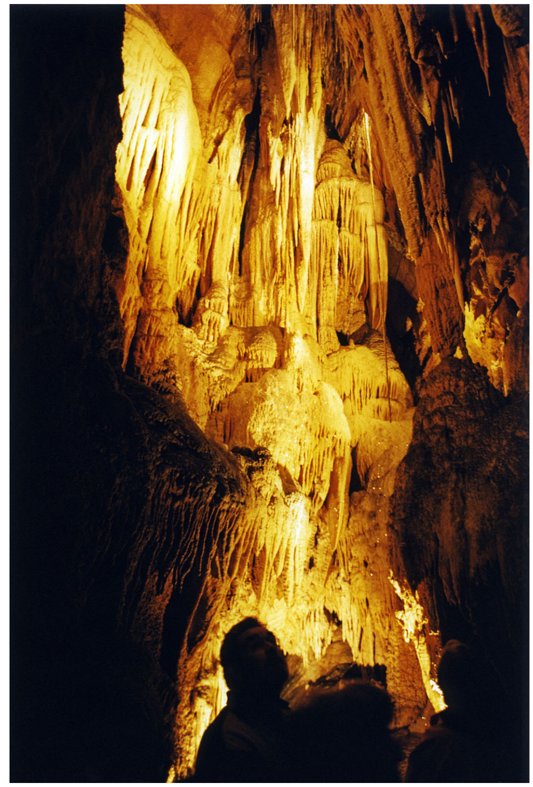
Anyway, let's talk about acids and bases and the mysterious pH scale. If you remember your basic (ha ha) chemistry, you'll recall that acidity, the strength of an acid or alkaline solution, is measured on a scale known as pH. A neutral solution, such as a glass of pure water, has a pH of 7. Acids have lower pH values, while bases (a base is essentially the opposite of an acid) have higher pH values. Tomato juice, a weak acid, has pH around 4. Lemon juice, a stronger acid, has pH around 2. Strong mineral acids like hydrochloric or sulphuric acid have pH approaching 1 or even 0. Strong alkaline solutions have pH approaching 14.

That's the way we were taught it in school. pH goes from 0 to 14, and neutral is right in the middle at 7. But why these numbers? Did some ancient chemist just decide 7 was his favourite number and go from there?

Water consists of molecules, each one containing two atoms of hydrogen, bonded covalently to one atom of oxygen (thus the descriptor which even many non-chemists know: H_2O). Water is a really good solvent, which means that it's really good at dissolving things. Dissolving is actually the breaking apart of chemical bonds between atoms. When you drop some table salt into water, the water acts to pull apart the sodium and chlorine ions present in the salt crystals, and gently separates them. Salty water is water with a bunch of free floating, loose ions of sodium and chlorine distributed through it. (I **talked about ions briefly here** when discussing ionic chemical bonding. That annotation also mentions covalent bonding.) Something like sugar is actually very different from salt, being made of quite large, covalently bonded molecules. These molecules assemble into the crystal structures we know as sugar crystals through a secondary, weaker bonding between the molecules. When sugar dissolves, the water pulls apart the weaker bonds, separating the sugar into individual molecules — but the molecules remain whole. As I said, water is really good at pulling other chemical compounds apart like this. Many, many chemical compounds dissolve in water, either into ions, or into separated molecules.

Even *water* dissolves in water a little bit.[3] The atoms of a water molecule can be pulled apart into a hydrogen ion (symbol H^+) and what's called a hydroxide ion (symbol OH^-). A hydrogen ion is a hydrogen atom with its only electron stripped off; in other words, it's a bare proton all by itself. A hydroxide ion is, as the name suggests, a hydrogen atom bonded to an oxygen atom, but with an imbalance in electric charge. Hydroxide ions have nine protons — one in the hydrogen atom and eight in the oxygen atom — but ten electrons, giving it an overall negative charge.

In a glass of water, some of the water molecules are dissolved into hydrogen ions and hydroxide ions. How many? I'm glad you asked! At any given temperature and pressure, the overall *concentration* of hydrogen and hydroxide ions in pure water is always the same. That is, the number of ions per volume of water. And because each water molecule that dissolves produces exactly one hydrogen ion and one hydroxide ion, the numbers of hydrogen ions and hydroxide ions are equal to each other. Chemists measure concentration of ions in solution with the unit *moles per litre*. A **mole** here is not a small furry mammal, but a fixed (and quite large) number of ions. You can think of the word "mole" as being like "million", only it's actually close to six hundred septillion (in the American or **short number scale**). The exact number comes about for



Mole Creek Karst caves. Another sort of mole, and these formations are produced by... acid.

historical reasons that are not important right now[4] — the important thing is that it's the right size to allow you to sensibly talk about chemical concentrations like 1 mole per litre, rather than six septillion ions per litre.

Now, if you take pure water (with part of it dissolved into ions), and add some more hydrogen ions somehow, then the excess of H^+ ions will force some of them to combine with some of the OH^- ions, thus reducing the concentration of hydroxide ions a bit. The resulting solution has slightly *more* H^+ ions than pure water, but slightly *fewer* OH^- ions than pure water. As it happens, the balancing point is determined mathematically by the following relationship: The concentrations of H^+ ions and OH^- ions, when multiplied together, *always give the same number*. As a simple example, if a volume of pure water contains 2 moles of H^+ ions and 2 moles of OH^- ions, then if you add 3 moles of H^+ ions here's what happens: 1 mole of the H^+ ions combines with 1 mole of the OH^- ions to give water

Wine fermentation vats. A practical use of acidity and careful pH measurement.

molecules. This leaves 1 mole of OH^- ions and 4 moles of H^+ ions, and the product

(1 mole OH^-) × (4 moles H^+)
= (2 moles OH^-) × (2 moles H^+)

This example is a little fuzzy because the extra water has been ignored — it's just to give you the idea of how the concentrations of H^+ and OH^- always multiply to give you the same number. And in fact the number, if expressed in terms of moles per litre, isn't nearly as big as 4. At room temperature it's actually very close to 0.00000000000001. In scientific notation, this is 10^{-14}. So in a glass of pure water at room temperature, the concentrations of both the H^+ and OH^- ions are very close to 10-7 moles per litre each, since $10^{-7} \times 10^{-7} = 10^{-14}$.

Those of you keeping an eye out for the "aha!" moment may have spotted it already. The pH of pure water is 7. The concentration of H^+ ions in pure water is 10^{-7} moles per litre.

If you add hydrogen ions to pure water — for example by adding the compound HCl, or hydrogen chloride — the concentration of H^+ ions increases, and the concentration of OH^- ions decreases in proportion. For example, the H^+ concentration might increase as high as 10^{-2} moles per litre, pushing the OH^- concentration down to 10^{-12} (the product if you multiply these together is still 10^{-14}). So the H^+ concentration of this resulting solution of hydrochloric acid is 10^{-2}. What's its pH?

If you said "2", well done. If you add more HCl, you can get the H^+ concentration as high as 10^{-1} or even 10^{-0} — and these acid solutions have pH of 1 and 0 respectively.

On the other hand, if you start with pure water and add hydroxide ions — for example by adding the compound NaOH, or sodium hydroxide — the concentration of OH^- ions increases, and the concentration of H^+ ions decreases in proportion. For example, the OH^- concentration might increase as high as 10^{-2} moles per litre, pushing the H^+ concentration down to 10^{-12} (the product if you multiply these together is still 10^{-14}). So the H^+ concentration of this resulting solution of sodium hydroxide is 10^{-12}. What's its pH?

I hope you said "12".

And that is why the pH scale ranges from 7 for neutral, to lower numbers for acids, and higher numbers for bases/alkalis.

Some interesting additional facts:

1. There's no reason to arbitrarily stop adding H^+ ions at a concentration of 10^{-0}. If you can force more HCl to dissolve, you can get a H^+ concentration of 10^{+1} moles per litre, which means a pH of $^{-1}$.

Cheesemaking. Also an application of acid - mixed with milk to make curds.

David Morgan-Mar

David Morgan-Mar is a research engineer living in Sydney, Australia. Currently working for **Canon Information Systems Research Australia** on image processing projects, he also finds time to write webcomics and role-playing game supplements, photograph at a professional level, follow cricket, travel the world, and be a drummer in a band.

How does he find the time to do all this?

I have extremely little spare time. I am always lamenting how I don't have enough time to do all of the stuff I want to do. What I do have is a creative urge. Ideas. The desire to make things, and do things, and learn things. What I have is a list of ideas for things I want to do, or make, or places I want to go. A big list. A really, really big list. I can't possibly do them all.

What I also have is the burning desire to make sure I damn well do at least some of the things on that list. I can't sit still in front of the TV. I'm always thinking about what cool thing I could be doing instead. So I'll run off in the ad breaks and fiddle with my photos in Photoshop, or write snippets of dialogue for comics, or bake some banana muffins. Despite not having enough spare time, I make the time to create things, because I can't bear the thought of not creating things.

People who are going out of their way to find the time to be creative and to make new things are taking steps to make something concrete out of the ideas and projects and creative desires locked inside their heads that other people would otherwise never get to see. They are making the most of their time. Go out and make the most of yours.

2. And of course there's no reason to use only whole numbers. If your H^+ concentration is $10^{-2.5}$ moles per litre, that means a pH of 2.5.

3. Remember that number of 0.00000000000001, or 10^{-14}, which is the number that the H^+ and OH^- concentrations give when multiplied together? Well, it's not *exactly* 10^{-14}. At 25° Celsius, it's actually $10^{-13.997}$. So the pH of pure, neutral water at this standardised temperature is not exactly 7, it's 13.997/2, or 6.9985. In practice this is not really important, and it's usual to just round it off to 7. Moreso because the number actually **changes quite substantially** with small changes in temperature. At 20°C the product is $10^{-14.167}$, and pure neutral water has a pH of 7.0835. These variations are usually ignored unless you're doing very precise chemical work involving concentrations and temperature changes.

There's a lot more to acids and bases than this. In particular, you can have acidic or alkaline solutions that don't involve H^+ or OH^- ions specifically, but have other ions that take their place. And of course I haven't even touched on aliens having acid for blood.

Notes

1. Imagine my delight when I learned via Carl Sagan's excellent television series ***Cosmos***, at about the age of 12, that **Io**, a moon of Jupiter, had volcanoes on it.

2. Some may argue that the rules of quantum mechanics are just as arbitrary, if not more so. On reflection, I can certainly understand that point of view, and to some extent agree with it. When learning all of this stuff for the first time though, I was willing to take on board the rules of quantum mechanics more readily. Possibly because it was more divorced from everyday reality than chemistry, so I figured there was little point questioning them too much. Of course, other scientists do question those rules as well, and so we delve ever deeper into the mysteries of how the universe works. This is why we build things like the **Large Hadron Collider**. Because we as a society aren't satisfied with being given arbitrary rules by nature.

3. The word "dissolve" here is being used loosely and figuratively. Technically the water molecules *dissociate*.

4. If you're curious, a mole was originally defined so that a mole of hydrogen atoms had a total mass of 1 gram. This meant that a mole of any one type of atom had a mass in grams equal to that atom's relative atomic weight compared to hydrogen. For example, oxygen has an atomic weight of 16, so a mole of oxygen atoms has a mass of 16 grams. This worked to the accuracies then known, but later definitions tweaked things slightly and this relationship is now a close approximation rather than being exact.