



Calorimetry: Crash Course Chemistry #19

Crash Course: Chemistry

<https://youtube.com/watch?v=JuWtBR-rDQk>

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====Introduction=====

Hydrochloric Acid: every chemist's frenemy, as terribly dangerous as it is terribly useful; it will burn your skin, your eyes, even your mucus membranes if you breathe in its fumes for too long. But HCL as an acid gives up its hydrogen pretty easily, which makes it good for making things like fertilizers and dyes and even table salt.

Then, there's sodium hydroxide, another substance that I wouldn't wish to be on my worst foe, although I'm glad we have it. You may know it as lye, an extremely caustic substance that's used for everything from clearing clogged pipes to purifying drinking water. It's a base. It readily accept the protons that acids release.

So what do you think will happen when I mix solutions of these two things together? Will they just cancel each other out and do nothing, or will they explode, or maybe they'll travel through time? Well, if you've been paying attention, you already know what's going to happen. They're going to undergo a neutralization reaction, which we've talked about before. These to potentially deadly substances will form harmless salt and water.

But the reaction will also have an effect that you can actually feel. It will release heat, and not just a little heat. Mixing concentrated acids and bases releases so much heat that it can result in an explosion...but I will show you how to produce a safe, but noticeable amount of heat with this reaction. To me, the coolest part of this is where the heat actually comes from. The energy used to exist as part of chemical bonds in the acid and the base. Just like a ball at the top of a hill, the molecules always move towards a lower energy state if they can, and that's just what they'll do. High energy bonds will break and lower energy bonds will form, the change in energy between those states you can actually feel the effects of, and that's pretty dang cool.

And what's even more awesome, if you ask me, is that we can actually figure out exactly how much heat will be released by this reaction.

(music: CrashCourse Chemistry)

====Pre-Experiment Discussion=====

Remember that measuring heat change is closely related to enthalpy, which we defined as the internal energy of a system plus the energy it uses to push the surroundings back and make room for its own pressure and volume. And in a constant pressure, like we have here at the surface of the Earth, that works out to be exactly the same as the heat that's absorbed or released by a reaction. Naturally, it can be very useful to know how much heat a chemical reaction absorbs or releases.

In addition to the exothermic hand-warmers that we have out there, there also endothermic chemical ice packs for treating injuries. The ability to calculate change in enthalpy is also what tells pilots how far the fuel in an airplane's tank will allow it to fly, which I personally am very interested in making sure they get right.

One of the ways we can calculate the change in enthalpy of a system is with Hess's Law, which you'll recall states that the total enthalpy change for a chemical reaction doesn't depend on the pathway it takes, but only on its initial and final states. It's often expressed in terms of Standard Enthalpy of Formation, that is, the amount of heat lost or gained when one mole of a compound is formed from its elements. That's how we figured out exactly how much heat my hand-warmers release.

But that's not the only way that Hess's Law can be used. The law itself says nothing about the standard enthalpy of formation. Any way that we can figure out the change of heat between the products and the reactants will work just as well, and that's where calorimetry comes in. Calorimetry is the science of measuring the change in

heat associated with a chemical reaction. And this may look like a plastic bottle inside a koozie, but it's actually a calorimeter. A calorimeter can be fancy and an expensive piece of hardware, or it can be simple. But no matter what it looks like, it's basically an insulated container that contains a thermometer and it can be made out of stainless steel or Styrofoam cups, but there really are no fundamental differences in how they work.

And you know the general setup by now: the chemicals in the calorimeter make up the thermodynamic system and everything else is the surroundings. The insulation minimizes the amount of heat that leaks in or out of the system so that we can be fairly confident that any heat transfer is part of the system, not the surroundings. The thermometer tracks the temperature change, which is part of the calculation we have to do, and there's usually some way to stir the solution to make sure that the reaction occurs fully.

====Experiment=====

Alright everybody, safety first, though I really should be wearing gloves... I'm gonna put 100 mL, also 100 grams, of HCL's one mole of HCL solution into my calorimeter here... (Mumbles). And now I'm going to put the same amount of sodium hydroxide solution. Before I do the reaction, I have to know our starting temperature, so I'm going to stick my thermometer in there and wait for a second to see what it does (it should be room temperature, it's been in the room for a long time). So, we are currently at, like, 20.8 degrees Celsius, so that's like, 294 Kelvin, and now I shall add my 100 mL of sodium hydroxide. The temperature, unsurprisingly, is rising very rapidly, and I'm doing something right now (which you should never ever do), which is stir with the thermometer, because if this happens in schools across the world, then there will be a million billion broken thermometers and the stuff inside these thermometers is not good. So never do what I'm doing.

Alright, the temperature should be stable by now, we have 28 point like 2 degrees Celsius. Now there's a simple formula that allows us to calculate the heat change of a reaction simply by measuring the change in temperature that occurs in a calorimeter. It says that the change in heat equals the specific heat capacity of the substance times its total mass times the change in temperature. Let's examine the parts of this.

====Calculations and Explanations=====

First of all, the heat change in the calorimeter is normally represented by a lowercase "q," but it can also be represented by change in enthalpy, or delta H, because remember that constant pressure (delta H) equals q, and constant pressure is almost always a good assumption for the duration of an experiment, or at least as long as we stay at the surface of the earth. For reasons that will become clear later, we'll sure delta H to represent the heat change for this experiment. Specific heat capacity, represented by a lowercase s, is the amount of heat required to raise the temperature of one mass unit, like a gram or kilogram, of a substance by 1 degree Celsius.

So it turns out that different amounts of heat create different temperature changes, like metals get hot really easily and cool down really easily; others like water require a lot of thermal energy to raise the temperature, and therefore have to release a lot of heat to cool down. I'm always wondering though, like, what does that really mean? Like, physically in the molecules, shouldn't heat raise the temperature of all substances equally? And why does water in particular have such a high specific heat capacity?



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Heat energy can do a lot of things besides just increase temperatures. Temperature, or the speed at which molecules bounce around, is just one way that atoms or molecules can absorb energy. Heat energy can also be absorbed by the breaking and formation of bonds between molecules, and as we'll learn in another episode, the extremely high specific heat capacity of water is due to the breaking and formation of hydrogen bonds that are associated with relatively small changes in temperature. And how do we know the specific heat capacity? Well, I am happy to report that some noble chemists have worked hard to determine the specific heat capacities of hundreds of substances so that we don't have to. We just have to look up the numbers in a table.

Okay, so specific heat capacity times mass times the change in temperature. The mass is important because the more mass of a substance we have, the more chemical bonds are present, and because energy is contained in chemical bonds, they have a big effect on how much energy we're able to absorb or release. And finally, there's the change in temperature. When doing calorimetry, we calculate a change in heat by measuring a change in temperature, but as we said a billion times before, heat and temperature are not the same thing. But please do not think that this thing is measuring heat because it's not! It's just that luckily, in this specific case, they are related by our handy little calorimeter formula.

Now you might not have noticed, but we are right at the interface between chemistry and physics here. Each science could claim ownership over this phenomenon, but the truth is humans made up the difference between chemistry and physics anyway. Thermodynamics, the study of heat, energy, and work, doesn't care about our little rules. Thermodynamics itself makes the rules of the universe. It is the ultimate law. So now you know, even though you might not have cared, but you should! Because it's good! It's all wiggly-wobbly bondy-wondy...

Alright! Enough talk, let's get out there, actually do some math here. Remember that the formula is $\Delta H = mc\Delta T$. The solutions we're using here are so dilute that almost all of their mass consists of water. Therefore, we can use the specific heat capacity of water. If we look that up on our table, we'll see that it is 4.184 Joules per gram degrees Celsius; I used 100 grams of each chemical for a total mass of 200 grams. And finally, we need the temperature change. If you remember, the temperature rose from 294.0 Kelvin to 301.4 Kelvin; the difference between these two is 7.4 Kelvin. It's a positive value because the temperature increased. Cancel out all the appropriate units and then bang on the calculator to get a final release of 6192.32 J, over 6.2 kilojoules of heat from the reaction.

Because this formula is based on temperature change and since the temperature increased, we end up with a positive result. But most importantly, it tells us the magnitude of the change in heat energy. So, I wonder how that compares to the amount we would predict using Hess's Law and the standard enthalpy of formation? Remember that we can look up the standard enthalpy of formation for all the products and reactants in the back of a textbook or online, the chemical reaction between hydrochloric acid and sodium hydroxide produces liquid water and sodium chloride. The standard enthalpy of formation for hydrochloric acid is -167.2 kJ per mole, for sodium hydroxide it's -469.15 kJ per mole, for liquid water it's -285.8, and for sodium chloride it's -407.27.

I'm not gonna do the mole calculations on-screen, but trust me when I say that we used 0.100 mole of HCL and the amount of NaOH. Because everything in the equation balances out, it's just a 1:1:1 ratio, we can assume that they all have the same amount of each product as well. If we plug these into Hess's Law and do the calculation, we found that the change in heat or enthalpy of the reaction is -5.67 kJ. The system is releasing or losing energy, so

the number is negative, but again it's really the magnitude that we wanna know. So there you go, the calorimetry formula gave an absolute enthalpy change of 6.2 kJ while Hess's Law gives a change of 5.67 kJ. So, why the difference?

Well, the greatest factor is probably that we used the specific heat capacity of pure water instead of the salt water that we actually created. We also didn't include the heat capacity of our calorimeter itself. The calorimeter walls and the thermometer were heated too, resulting in some of the produced heat not being accounted for. The insulation of the calorimeter is obviously a bit light, which allowed some heat to escape entirely and that's another major factor. Even so, I'd say we did pretty well, the important thing is that it showed us what we needed to see even though it was just a little plastic bottle in a koozie. For a quick simple method, the calorimeter got us pretty close to the calculated value.

If we were calculating the amount of a particular fuel we would need to travel to Mars or inventing a cold pack that won't give you frostbite, we'd wanna use a more sophisticated system and work more carefully, but this was pretty cool for our purposes.

Thanks for watching this episode of Crash Course. If you paid attention, you learned that we don't necessarily have to use standard enthalpies of formation to solve Hess's Law, you learned what a calorimeter is, that calorimetry is another way to investigate heat changes in chemical reactions, and that specific heat capacity tells us how much heat energy affects the molecules in a substance without changing its temperature. And finally, you learned some potential sources of error related to calorimetry.

The episode of Crash Course Chemistry was written by Edi Gonzalez, the script was written by Blake de Pastino and our chemistry consultant was Dr. Heiko Langner. It was filmed, edited, and directed by Nicholas Jenkins, our script supervisor was Caitlin Hofmeister, and our sound designer is Michael Aranda. And, of course, our graphics team is Thought Cafe.