[Hank takes a deep breath and begins to blow up a balloon]

Gas! It's all around you. It's in space. It's on Mars. It's dissolved in your blood, and in your soda. It's everywhere. And it's easy to forget that we're submerged in an ocean of gas, but it's there all the time. You can feel it if you wave your arms around. [Hank begins to wave his arms up and down.] Can't look cool while you're feeling it but you can feel it. It's there. Those little molecules and atoms bumping around against your hands as you wave them around. Feel it? Are you doing this?

I've got good news and bad news about gases. First the good news, when they're behaving themselves it is extremely easy to describe their behavior theoretically, experimentally and mathematically. The bad news is, they almost never behave themselves.

[Intro Music Plays]

(00:50)

=====The Ideal Gas Law=====

The first mathematical description of a behavior of a gas was a link between pressure and volume. In a closed system like the inside of this balloon, when we decrease the volume of the balloon the pressure inside goes up. And if we could somehow expand the balloon, then the pressure inside the balloon would go down. If I keep pushing on it the pressure inside might go so high that it'll break. [Hank continues to press against the balloon harder and harder] I hope...I can't do it. It's a very strong balloon!

The relationship here is a simple one. When you multiply the pressure and volume together, you get a constant. As long as the temperature and amount of gas stays the same. So does that constant. It's called Boyle's Law, and it was a pretty big deal back in the 1600s. It's also, one of the greatest scientific mis-attributions of all time.

(01:35)

=====Everyone but Robert Boyle=====

Robert Boyle was a super rich Englishman, raised in Ireland. His father was so rich that he paid another family to raise his children. I guess because he was too busy administering lands or something. Boyle had lots of great ideas about science and chemistry. His most important one, and this is arguably even more important than Boyle's Law, being that chemists should publish papers not on what they feel is correct, but rather on theories that have been backed up by experimentation.

Richard Towneley a wealthy, but considerably less wealthy, Englishman struck up a relationship with Boyle. Telling him about some of his work that would disprove one of those "But it feels right" kind of chemists. Boyle published the paper mentioning that work, which he called Towneley's Hypothesis. But which ended up, because of Boyle's superior scientific standing and possibly his wealth, being called Boyle's Law. But here's the really messed up thing, the experiments that led to the creation of this theory were actually done largely by Towneley's family friend and physician, Henry Power, who's not a member of the aristocracy at all. He was just a working class scientist. Power was working on a publication that would have snared him the position as discover of the relationship between the pressure and volume of a gas. But Boyle, having discussed the ideas with Towneley privately, published his first, attributing Towneley as the sole researcher, ensuring that Power's contributions were all but lost to history. Henry Power's Wikipedia page didn't even mention Boyle's Law until a few weeks ago, when I personally added a paragraph about it, with proper citations of course.

But no matter who thought it up or who it got named after, Boyle's Law is pretty cool. For a given amount of gas at a constant temperature, pressure times volume always equals the same number. But where is that constant coming from, and why is it different for different amounts of gas at different temperatures? Well it was more than a hundred years before we'd figure out the answer to those questions, with the help of a Frenchman Jacques Charles and our old, Italian house-elf friend Amedeo Avogadro.
Charles and Avogadro created equations much like Boyle's law with two features of a gas being linked directly together by constants. Charles discovered that volume divided by temperature equals a constant as long as the pressure remains the same. And then Avogadro figured out that volume divided by the number of moles in the container at a constant pressure and temperature gave yet another constant.

But here's the crazy cool thing, all of these scientists were basically dealing with a different form of the same equation. An equation that we must never forget, and is gonna be stuck in my head until I die, and here's how it works. Pressure times volume is equal to the number of moles of substances times a constant times temperature. P V equals n R T: The Ideal Gas Law, which works for all gases as long as they behave themselves. Now here's the cool part, using this equation we can show how all of these chemists were dealing with the same relationship. They were just clumping various variables together in different orders.
All of the chemists we just mentioned: Charles, Avogadro and Boyle (or more properly Towneley and Power), figured out their contribution to the Ideal Gas Law experimentally. But more interesting to me, is that it can be understood theoretically.

First, we have to understand what each of these variables actually mean. In that same way the atoms and molecules that make up gases are bouncing against things, applying pressure to them. This balloon is inflated because the molecules are bouncing around inside of it, bumping into the inside of the balloon harder than the molecules bouncing off the outside of the balloon. Scientists generally measure pressure with the S.I. unit of force: Newtons per area, meters squared, which is shortened to pascals. But since pascals are so tiny we either use kilopascals or we use the pressure here on earth at sea level, that we call one atmosphere or one atm. Completely by chance, one atmosphere is equal to 101325 pascals but that's so close that we often just say that one atmosphere is 100,000 pascals or 100 kilopascals.

Volume is the amount of space particles have to exist inside of. So yeah, that makes sense, when the volume goes down, the pressure goes up, because there are more particles in a smaller space, and they'll each hit the walls more often.
N is simply the amount of gas, the number of moles in the system. Here I am decreasing the amount of gas in the system and in response the volume is decreasing, obviously. But so is the pressure inside the balloon.
R in the Ideal Gas Law is called the Universal Gas Constant. Even though, as we will see in a coming episode, it is neither universal or constant. It's 8.3145 liters kilopascal per kelvin mole.
Temperature, is experienced by you and me as hot or cold but at the atomic level it's kinetic energy. Literally, how fast or slow the average particle is moving. So if temperature goes up, so will the pressure as the particles are moving faster and thus will run into the sides of the container more often.

So now we know about all of the little bits of the Ideal Gas Law, so let's take a look at it in action.

(06:16)

=====Ideal Gas Law to Figure Things Out=====

We here at crash course generally like to be very safe. This is a little bit of overkill here. I put a little bit of water into this soda can and now I'm boiling it. So instead of atmosphere gas in this can right now there's water vapor, and it's hot and all the molecules are zipping around like crazy. We pick it up and we plop it down inside of that...ooooo [can collapses]....and it crushes itself.
So what just happened there. Well, let's see what the gas law can tell us.
So which of these things are changing? Starting on the right hand side: R, is constant, so that can't change. The temperature of the gas though, that definitely changed; it drops like mad when it's exposed to the ice water. *N* is decreasing too as water vapor is condensing into liquid water, it thus disappears from the gas phase. So the next result on the right hand side is a decrease, and that means that the left hand side has to have a decrease too.
So on to the left hand side. The pressure does indeed drop because the lower temperature makes the molecules move more slowly, thus bumping into the sides of the can a lot less than before. The volume drops too, but not quite for the reason you might think. It's really that the pressure inside the can goes so low, that the pressure outside the can, the atmospheric pressure, literally crushes the can.
Now I understand that you probably don't think this is as cool as I do, but understanding the physical reality of atoms and molecules smacking into things is a special kind of beautiful for me. It's also pretty cool that if you know any three things about a gas, you can figure out the fourth using the ideal gas law.
Of course, not all gases behave ideally, and all gases deviate from the law at low temperatures or high pressures. But we'll save that discussion for a later episode.

(07:46)

=====Jargon Fun Time=====

Jargon fun time. STP means standard temperature and pressure which according to the lords of chemistry is zero degrees Celsius and 100,000 pascals or 100 kilopascals. One mole of any ideal gas takes up 22.4 liters of space at STP, which is a fact that can simplify a lot of calculations. Absolute zero is the temperature at which all movement of all particles stops. It is zero kelvins or -273.15 degrees Celsius. And that's all for this episode.

=====Summary=====

Thank you for watching Crash Course Chemistry. If you were paying attention you learned about how the work of some amazing thinkers combined to produce the Ideal Gas Law; how none of those people were Robert Boyle, and how the Ideal Gas Equation allows you to find out pressure, volume, temperature or number of moles as long as you know three of those four things. And you learned a few jargon-y phrases to help you sound like you know what you're talking about.

=====Credits=====

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