Shedding Light on Atoms Episode 3:
The Discovery of Atoms

The Shedding Light on Atoms series gives students the perfect introduction to the world of atoms. Using amazing demonstrations and animations we take students on a journey of discovery to explain not just what we know about atoms, but also how we know what we know about atoms!
In Episode 3, The Discovery of Atoms, we demonstrate (using copper) how elements can join together to form compounds and how compounds can be broken back down into the individual elements that make them up. We take a look at the first (fairly) accurate list of elements ever published and explore the Law of Conservation of Mass. We crush some aluminium cans to show students what causes air pressure and then explain, using lots of different examples, the experiments that led directly to the discovery of atoms.

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Part A: Introduction: a brief recap on atoms, elements and compounds
Part B: Copper and Copper Oxide: We demonstrate how copper can combine with oxygen to produce copper oxide and how copper oxide can be broken back down into copper and oxygen. We explain how blast furnaces produce metals like iron from iron ore.
Part C: Lavoisier's List of Elements: The first (fairly accurate) list of elements was published by Lavoisier in 1789. The Ancient Greek 4-element theory was laid to rest. We explain what fire is.
Part D: The Law of Conservation of Mass: Among other achievements, Lavoisier proposed the Law of Conservation of Mass. In any chemical reaction, the mass of the reactants equals the mass of the products. Numerous chemical reactions are shown to demonstrate.
Part E: Some Physical Evidence: In the 1700s, experiments involving air pressure suggested that air was made of tiny, rapidly moving particles. We demonstrate and explain what air pressure is and why it occurs. However, though air pressure alone could not prove that atoms existed, it did lead many towards a belief in atoms.
Part F: Atoms are Discovered: When compounds were analysed carefully, it was realized that they always show a fixed ratio of the weights of the elements that make them up. John Dalton used this data to propose the existence of atoms. Later, Jons Berzelius came up with our "modern" system of chemical notation.

The images shown below are screen grabs from the program and the text is more or less the program's script.

Part A: Introduction

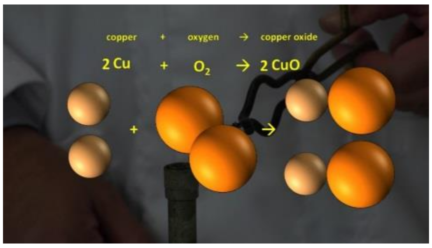
Bricks, stone, steel, glass…everything in fact is made of atoms. Atoms are tiny, way too tiny to be seen individually, so how were they discovered?
Well, we've seen that experiments in the 1700s revealed to scientists that some substances, like hydrogen and oxygen could not be broken down into anything simpler because they weren't themselves made up of anything else. These kinds of substances were called elements. Other substances though, called compounds, are made of elements which chemically join together. carbon dioxide and magnesium oxide are just two examples.
By performing lots of experiments, scientists in the late 1700s were getting very close to discovering atoms.
Let's look at one more example that will help illustrate how substances can combine chemically to form something new and then come apart chemically to reform what we started with.

Part B: Copper and Copper Oxide

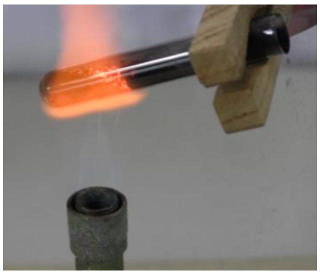
This is copper metal, which we use to make electrical wiring and water and gas pipes. If I take a small amount of copper and heat it really strongly, it slowly turns black.
The copper chemically combines with oxygen in the air to produce the black substance which we now call copper oxide (CuO).

Copper metal on the left, copper oxide on the right.
We know it's oxygen that the copper combines with because if we heated it in an enclosed container without oxygen, it wouldn't turn black.

The equation for the chemical reaction is copper + oxygen → copper oxide
$Cu + O_2 \rightarrow CuO$
Let's balance the equation.



We have 1 Cu atom on the left and 1 Cu atom on the right, so our Cus are balanced. However, since we have 2 O atoms on the left, we in fact form 2 CuOs, so we need to put a 2 in front of the CuO.
Now we have 2 Cu atoms on the right, so we need to go back and put a 2 in front of our Cu on the left.
The equation is now balanced.
$2Cu + O_2 \rightarrow 2CuO$

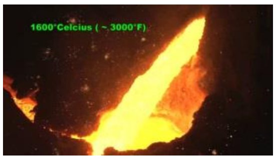


So, is our pure shiny reddy-brown copper metal gone forever? Is there any way of getting the copper back, of somehow pulling the oxygen and the copper apart again? Well, of course there is. With copper it's actually pretty easy. With many other metals it's really hard.

If I take some carbon powder, and mix it with some powdered copper oxide, basically the same stuff I just produced, but crushed into a powder, and then heat the mixture again, a different chemical reaction occurs and the reddy-brown copper metal starts to reform in the test tube. The copper oxide powder, which was made of copper and oxygen atoms which had chemically joined together, is being broken back down into copper metal and oxygen. The oxygen quickly combines with the carbon and forms carbon monoxide, an invisible gas that flows

out of the test tube.
The equation can be written as copper oxide + carbon → copper + carbon monoxide.
In symbols $CuO + C \rightarrow Cu + CO$.
So while copper oxide can be broken down, no chemical reaction ever performed by any of the scientists in the 1700s showed that copper or carbon can be broken down. They were pretty certain therefore that copper and carbon were elements, and we now know that they were right.

Now let me quickly just mention that the reaction you've just seen is basically how many metals are actually produced in industry, but on a huge scale.
Iron for example isn't found naturally as iron metal, because the earth's iron atoms are usually chemically joined to oxygen atoms in a reddish mineral called iron oxide. Iron oxide is obtained from iron ore mines. Iron ore is the name given to the rocks from which iron can be extracted at a profit by mining companies. After the iron oxide is mined and purified, it's fed into huge blast furnaces along with carbon, which they get from coal mines. They also pump in oxygen.
A series of chemical reactions takes place, similar to the copper-producing reaction I showed you, which separates the iron atoms from the oxygen atoms, resulting in the production of iron, liquid iron in fact since blast furnaces operate at temperatures of more than 1600°Celsius (~ 3000°F). The iron is then used to make steel, the most commonly used metal in the world. (Steel typically consists of more than 98% iron. Small amounts of carbon and other metals are added to iron to produce steel.)

Part C: Lavoisier's List of Elements

In 1789, after years of doing his own research, and also organizing the research of others, Lavoisier published a list of substances that couldn't be broken down into anything simpler, that is a list of "elements".
On his list he included 3 gases: oxygen, nitrogen and hydrogen; 3 other non-metals: sulphur, phosphorus and carbon; 2 metalloids: arsenic and antimony; and 15 metals: Bismuth, Cobalt, Copper, Gold, Iron, Lead, Manganese, Mercury, Molybdenum, Nickel, Platinum, Silver, Tin, Tungsten, and Zinc.

He wrote that people should forget about the 4-element theory because it wasn't based on any scientific observations. The evidence suggested that the world was not made of just 4 elements; it was made of far more. These elements like copper and oxygen either existed on their own, or they combined together to form compounds, like copper oxide and water.

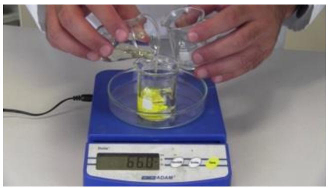
The elements we've seen so far in all our experiments are hydrogen, oxygen, carbon, copper, and magnesium (although in the 1700s magnesium hadn't been discovered). The compounds we've seen are water, carbon dioxide, hydrogen peroxide, (which was also unknown to the scientists in the 1700s), limestone (or calcium carbonate), hydrochloric acid, magnesium oxide and copper oxide.

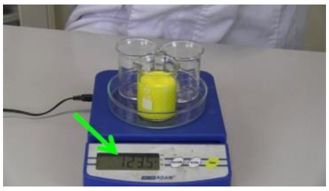
Now Lavoisier also included some substances on his list of elements which were later shown to be compounds because at the time no-one knew that they were made of more than one element and they couldn't be broken down into anything simpler.

However, Lavoisier acknowledged that his list might not be perfect. These things were elements only as far as they could tell through experiments he said. If someone comes up with a way to break down any of the substances on his list of elements and proves through experiments and observations that they're actually compounds, the list will change.
He really was a fantastic scientist! (Thanks)
The ancient Greek four-element theory had finally been laid to rest.
Science wasn't about referring back to what some ancient Greek philosopher had written. It was about making observations and measurements, and setting up experiments. If the writings of some ancient Greek philosophers didn't fit with experiments and data, then even though they had been famous for thousands of years, their beliefs had to be discarded!

So Earth, Water and Air weren't elements, but what exactly is fire?
Well, whenever something gets really really hot, like this iron rod being heated by an oxyacetylene torch, it starts to glow.
Now most chemical reactions produce heat. When things burn, the gases produced are usually so hot that they glow. Fire is just the red hot gases coming from a burning fuel. As the gases get further away from the fuel, they cool down and stop glowing.

Part D: The Law of Conservation of Mass
Now with careful measurements and experiment after experiment, Lavoisier also came up with the so-called Law of Conservation of Mass.
He was able to prove that in any chemical reaction the mass of the substances that were being produced was exactly equal to the mass of the substances that had reacted.
Stuff never just disappears into thin air and it never just appears out of nowhere!



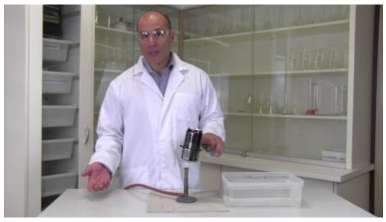


As an example, let's look at potassium iodide dissolved in water, and lead nitrate dissolved in water. Together with the glassware, their total mass is 123.5 grams.
If we then mix the two substances, a chemical reaction occurs and we see a completely new substance form that wasn't there before: lead iodide. Potassium nitrate also forms but it stays dissolved in the water. However, as you can see, the total mass of everything combined is unchanged: 123.5 grams.
The equation for the reaction is
potassium iodide + lead nitrate → lead iodide + potassium nitrate
$2KI + Pb(NO_3)_2 \rightarrow PbI_2 + 2KNO_3$.
The Mass of the Reactants = The Mass of the Products
The Law of Conservation of Mass states that the combined mass of the reactants, that is, the chemicals you start with and which chemically react, is exactly equal to the mass of the chemical reaction's products.
Now that we know about atoms, it's fairly obvious why.
Whatever atoms you put into a beaker are still there after the chemical reaction has taken place. The atoms just rearrange themselves to form something new, but none of them could have just disappeared and no new atoms could have just appeared.

So if you heat something up and the product gets heavier as was the case with the Magnesium we saw in our last episode, you know it must have combined with something in the air, even if you can't see it.
This Law of Conservation of Mass was another major breakthrough because it's not immediately obvious. When you burn wood for example, the mass of ash left over is much smaller than the mass of the wood you started with. But that's only because most of the mass is given off as smoke and invisible gases (mostly carbon dioxide and water in the form of steam).

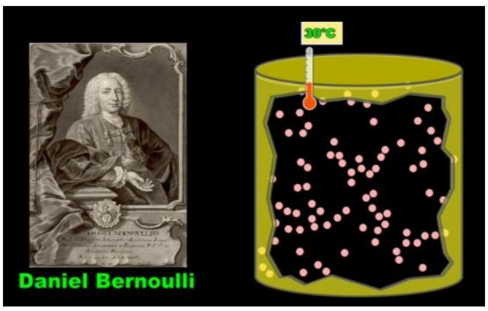
This is copper carbonate. Its mass together with the test tube is 41.312 grams. After gentle heating the green powder turns into a black powder called copper oxide. It looks like it's melted, but in fact the powder is moving around because an invisible gas is being produced. If I now reweigh everything, I find that the mass has decreased to 40.358 grams, a loss of 0.954 grams.
If the products of a chemical reaction seem to get lighter in a chemical reaction it means that something must have been given off, even if you can't see it.
In fact the equation for the reaction is copper carbonate produces copper oxide (the black powder) and carbon dioxide gas. $CuCO_3 \rightarrow CuO + CO_2$
The invisible carbon dioxide gas flows out of the test tube.
Once the copper carbonate is all gone and no more carbon dioxide is being produced, the black copper oxide powder just settles down and stops moving around inside the test tube.

Part E: Some Physical Evidence



Now many scientists did start to suspect after all these experiments that everything must be made of tiny tiny individual and indivisible particles, or in other words atoms, which join together in groups.
This can has a small amount of water in it. If I heat the can up, the water boils and the steam comes out of the can.

To allow you to see it more easily, we shot this scene with some dark paper behind the can.
If I then plunge the can upside down into a tub of cold water… the can crushes.
We often think of air as something that just kind of floats around, but it's actually a little more complicated.
Experiments like this one in the 1700s, not exactly the same of course but similar, suggested that the air is made of tiny tiny particles that constantly bounce into each other and onto things around them. These collisions of the trillions of tiny particles on a surface cause air pressure. We now know that the particles, the atoms, move hundreds of metres per second, but travel only a few tiny tiny fractions of a millimetre between each collision (on average about 100 billionths of a metre).
We also often think, like they did before the 1700s, that air, and gases generally, don't weigh anything, but they do. Just because these balls are flying through the air and bouncing around all over the place, doesn't mean that they have no mass or weight. Likewise, the atoms that make up gases also have mass, and every time they collide with other atoms, they exert a small force, which as I said, is what causes air pressure.
(I wonder if fish think that water doesn't weigh anything, since it just kind of floats around.)
Normally the air pressure inside the can is equal to the air pressure outside the can.
However, in this situation, the steam pushes most of the air out of the can and then, when the can is tipped upside down into the water, the steam cools down and turns back into water, leaving almost nothing in the can. No steam and very little air, so the air pressure inside the can is very low. However, the trillions of particles of air on the outside of the can are still there exerting normal air pressure and so they crush the can.
Tipping the can upside into the water is only necessary to stop air getting back into the can. Placing a lid over a can with boiling water in it accomplishes the same thing. As soon as I remove this can from the hotplate and place a lid onto it, the steam inside it, which has already pushed most of the air out, starts to cool back down and condenses into water which takes up less space than steam. The pressure inside the can drops right down, so the air pressure outside the can crushes the can.



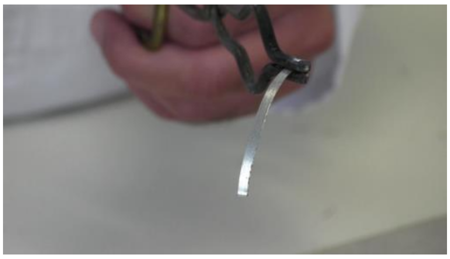
The idea that air is made up of rapidly moving particles which cause air pressure was formulated by Swiss scientist Daniel Bernoulli in 1738, but whether these particles were made of atoms or were atoms could not be determined.

Lavoisier acknowledged that atoms may exist, but he insisted that scientists should not promote and push theories that might be correct. Science required a really strict analysis of experiments and observations. In other words they needed more evidence.

Unfortunately, he never lived to see the evidence. While he had been conducting all his experiments he also worked as a tax commissioner for the French King. When the French Revolution occurred in the 1790s, the king was overthrown and many of his former employees were arrested, among them Antoine Lavoisier. Despite all that he had done, he was beheaded by the guillotine in 1794 at the age of 50.

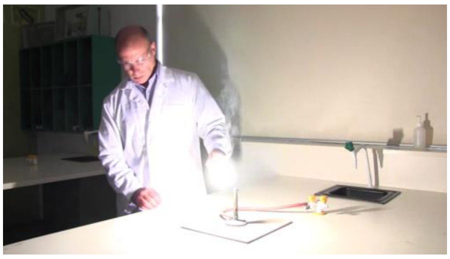
The first real evidence for the existence of atoms came only about a decade later.

Part F: Atoms are Discovered

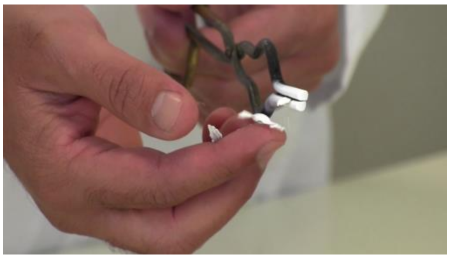


This is a piece of magnesium metal. Magnesium is very flammable, but you need to heat it to a fairly high temperature before it starts to burn.

Once it does start burning though, it burns with a really hot white flame at a temperature of more than 3000 degrees Celsius. The product of the chemical reaction is magnesium oxide, a white powder.



Though it might be interesting to observe, we can't really get much information from an experiment like this. A lot of the magnesium oxide literally goes up in smoke as the magnesium burns, so if we weigh the left over magnesium oxide, it's not going to tell us much.

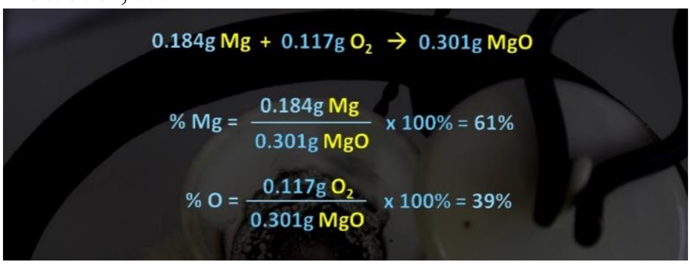


In our last episode, we saw that if we heat magnesium slowly in a crucible and try to trap any of the smoke produced, we can confirm that the magnesium chemically reacts with the oxygen in the air and the white magnesium oxide powder produced is heavier than the original strip of magnesium.

Let's look at the figures again: 0.184 grams of Magnesium combined with 0.117 grams of oxygen and turned into 0.301 grams of magnesium oxide.

Last time we just looked at the fact that the Magnesium oxide is heavier than the original strip of Magnesium since the Magnesium chemically combined with oxygen from the air.

However, …



These figures can tell us a lot about magnesium oxide itself.

To analyse the figures though we have to do some maths for the next few minutes.

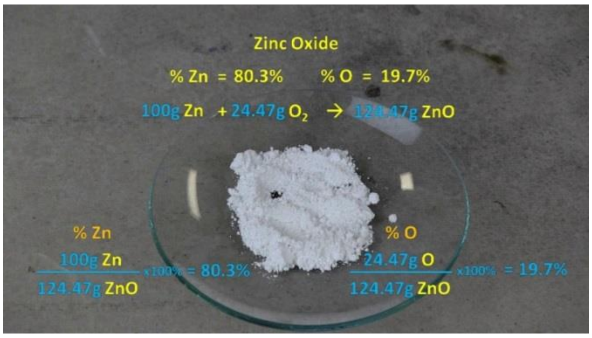
As a percentage, magnesium makes up 0.184g of the 0.301g of magnesium oxide which is about 61%, while oxygen makes up 0.117g of the 0.301g of magnesium oxide which is 39%.

In fact if I had done my experiment even more accurately, I should have found it to be 60.3% Magnesium and 39.7% Oxygen.

In the late 1790s and early 1800s, French Scientist Joseph Proust performed experiments on lots of different compounds and found that the proportion by weight of the elements that make them up was always the same.

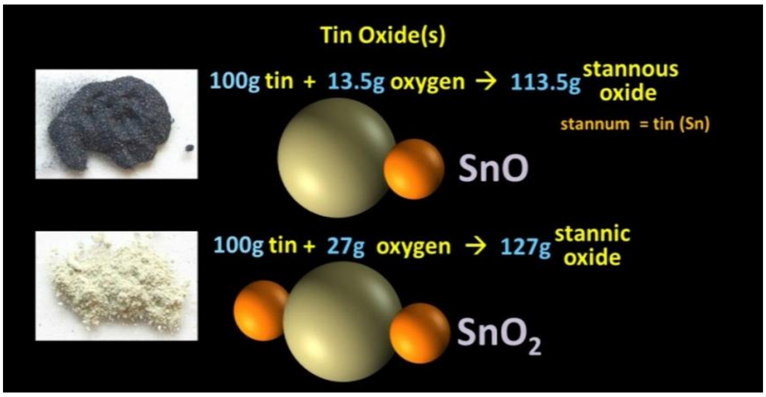
If you do the same experiment as me with magnesium, anywhere in the world, you'll get results much like mine: The magnesium oxide you produce should be about 40% oxygen and about 60% Magnesium.

This is zinc oxide. By weight, zinc oxide is always 80.3% Zinc and 19.7% oxygen.



If exactly 100 grams of zinc metal reacts with oxygen the mass of oxygen it reacts with will be exactly 24.47g and exactly 124.47 grams of zinc oxide will be produced.
The percentage of zinc in the zinc oxide is 100g/124.47g which is 80.3% while the percentage of oxygen in the zinc oxide is 24.47g over 124.47g which is 19.7%. This will always be the case.
Proust even found that there were two types of tin oxide, but each one still had a fixed proportion of tin and oxygen.

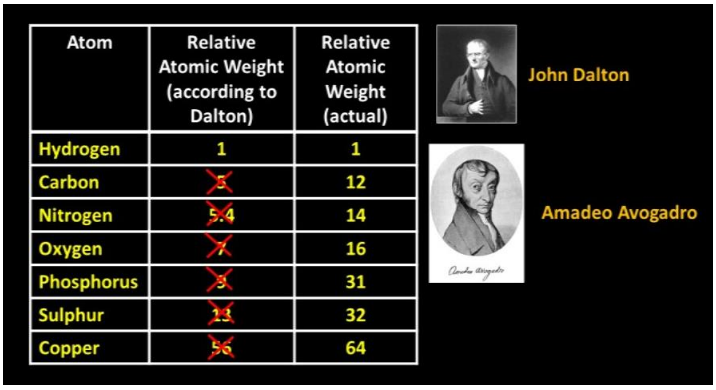
In the early 1800s English scientist John Dalton was analysing Proust's results and also performing his own experiments and he came up with the reason for why compounds always showed fixed ratios of the weights of the elements that make them up.
Let's look at the tin oxides again.
In the first type, 100 grams of tin would combine with 13.5 grams of oxygen to produce 113.5 grams of what was named stannous oxide. Stannum is the Latin name for Tin, and it's where Tin's atomic symbol of Sn comes from.
In the second type of tin oxide, 100 grams of tin would combine with 27 grams of oxygen to produce 127 grams of what was named stannic oxide.



Dalton noticed that the number 27 is exactly double 13.5, and he proposed that it must be because both tin and oxygen were made of atoms.
In the first type of tin oxide, each tin atom combines with one oxygen atom, in modern notation we would write its formula as SnO, while in the other type of tin oxide, each tin atom combines with two oxygen atoms, so it's formula can be written as SnO_2.
Not only did Dalton's brilliant analysis demonstrate the existence of atoms, his figures showed that tin atoms must be about 7 times heavier than oxygen atoms.
In the first type of tin oxide for example, there are equal numbers of tin atoms and oxygen atoms, but the tin atoms have a mass of 100 grams which is about 7 times the mass of all the oxygen atoms, so each individual atom of tin must be about 7 times heavier than each individual atom of oxygen.
Dalton reasoned, based on the data, that atoms are indestructible and that that they don't split into pieces in chemical reactions, they simply rearrange themselves.

Of course, Dalton didn't analyse just one compound and he had no idea how heavy each individual atom was but by performing lots of experiments he was able to estimate how heavy the atoms of lots of different elements were compared to each other.

Because hydrogen appeared to be made of the lightest atoms, he assigned hydrogen atoms a weight of one.
Using the results of his experiments, he calculated that carbon atoms were 5 times heavier than hydrogen atoms, nitrogen atoms 5.4 times heavier, oxygen atoms 7 times heavier and so on.
These figures were called relative atomic weights because they were the weights of each atom in relation to (or compared to) hydrogen atoms.



Atom	Relative Atomic Weight (according to Dalton)	Relative Atomic Weight (actual)
Hydrogen	1	1
Carbon	~~5~~	12
Nitrogen	~~5.4~~	14
Oxygen	~~7~~	16
Phosphorus	~~9~~	31
Sulphur	~~13~~	32
Copper	~~56~~	64

Unfortunately, most of Dalton's figures turned out to be fairly inaccurate. Dalton didn't realize for example that the oxygen atoms in oxygen gas and the hydrogen atoms in hydrogen gas always come in pairs. He also made an error in thinking that water's formula was HO instead of H_2O.

In 1811 though, Italian scientist Amadeo Avogadro, who was experimenting with gases using equipment similar to Lavoisier's, worked out the correct nature of hydrogen and oxygen gas and the correct formula for water and this led to far more accurate figures for the relative atomic weights of atoms.

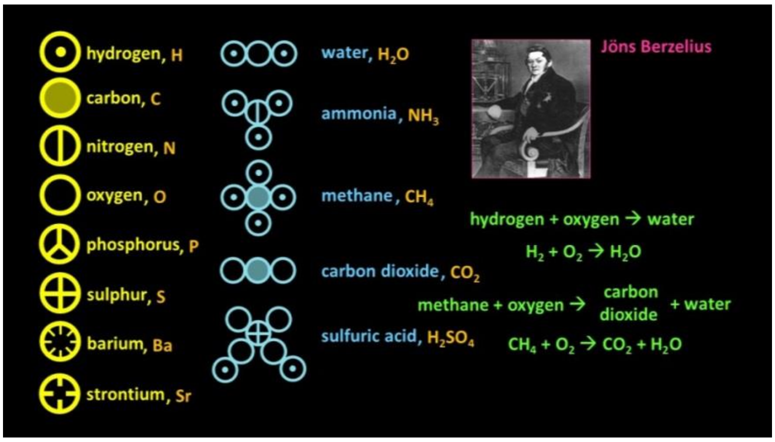
It turned out that carbon atoms are 12 times heavier than hydrogen atoms, nitrogen atoms 14 times heavier, and so on.

To represent his atoms, Dalton used circular symbols with different patterns inside them.

To show compounds he drew the symbols next to each other.

The problem with his symbols, though, was that they were too hard to remember. In the 1810s, Swedish scientist Jöns Berzelius came up with the system of using letters as atomic symbols and chemical formulas to represent compounds. He was also the first person to start writing chemical equations.

So our modern system of chemical notation is actually more than 200 years old.



So that's how atoms were discovered. They couldn't be seen individually, but a detailed study of chemical reactions showed that they definitely existed.

However, there was still a lot to learn. How many elements were there and what made atoms join together to form compounds? And why did atoms join together only in certain combinations? H_2O existed, but why was there no such thing as H_3O or H_4O for example?

Our journey of discovery is far from over and we'll continue it in our next episode. See you then.

Credits:

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