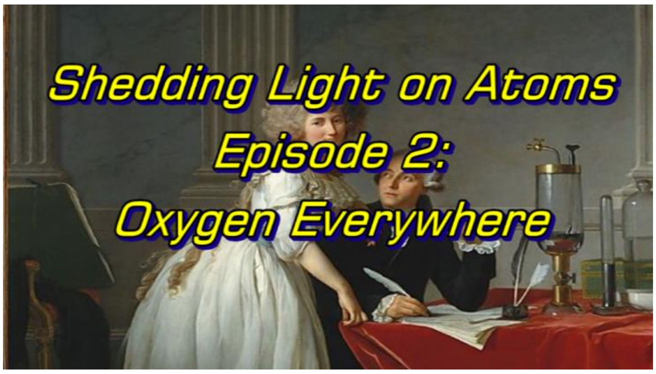
Shedding Light on Atoms
Episode 2:
Oxygen Everywhere



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 2, Oxygen Everywhere, we discuss how the discovery of oxygen helped to accelerate the study of chemistry. We examine how hydrogen was discovered and how it was discovered that water is formed when hydrogen and oxygen chemically join together. We then look at oxygen's role in producing metal oxides from metals and its role in respiration. The history of the discoveries relating to oxygen is blended in seamlessly with modern chemistry to give students a really strong foundation in the scientific method and in the steps which led to an atomic theory.

Contents:
Part A: Introduction: A brief recap on Episode 1, including an explanation of what elements and compounds are.
Part B: The Discovery of Hydrogen: Hydrogen is a flammable gas and produces water when it reacts with oxygen. It is explosive if it burns in the presence of lots of oxygen. Hydrogen was once used in airships, but the Hindenburg disaster ended that practise. It is still used as rocket fuel.
Part C: Nitrogen and the Atmosphere: Using magnesium's reaction with oxygen, we take a look at how Antoine Lavoisier determined that air is made up of about 20% oxygen gas and 80% nitrogen gas. We explain how oxygen's role in keeping us alive was discovered.
Part D: Breaking it Down: During all the experiments performed by scientists in the late 1700s, they realized that certain substances could be broken down into simpler substances and certain substances could not. This distinction between elements and compounds was a huge step forwards towards the discovery of atoms.

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

Part A: Introduction

Atoms. Atoms are the tiny tiny building blocks that make up everything. But how do we know about atoms if they're too small to see.

In this series of programs, we're answering that question while we learn the basics of Chemistry.

So what have we learned so far?

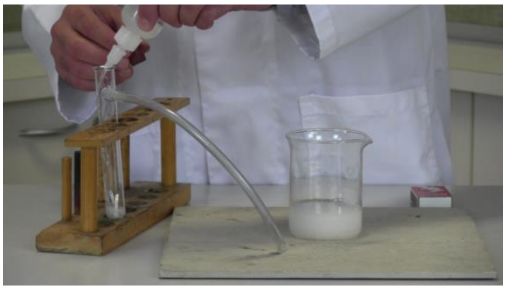
In Episode 1 we learned that scientists now use atomic symbols to represent all the different types of atoms. Anything made up of only 1 type of atom, like copper is called an element. Compounds, substances made up of two or more different atoms which have chemically joined together are represented by chemical formulas. Chemical equations are used to show the reactants in and the products of chemical reactions.

However, we still haven't explained how atoms were discovered, but that's where we are heading.

We saw that for a long time people thought that everything on Earth was made of four basic components, but in the 1700's, scientists discovered that air is a mixture of lots of different gases. The gases we looked at were carbon dioxide and oxygen, which were both discovered in the mid-1700s.

Part B: The Discovery of Hydrogen

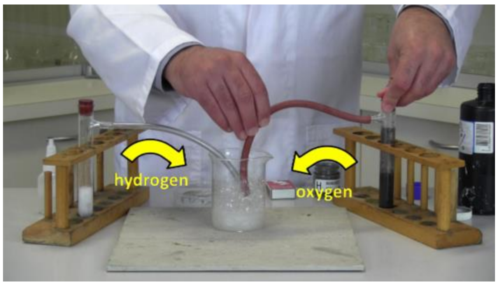
In the 1760s, English Scientist Henry Cavendish was experimenting with metals and acids and discovered another gas which was different again.

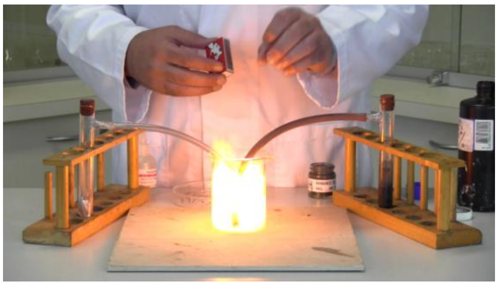


We'll create this gas by reacting magnesium metal with hydrochloric acid.

Like the two reactions we saw in Episode 1 that produced CO_2 and O_2, this one also produces bubbles of gas as soon as the two chemicals come into contact.
Henry Cavendish used zinc in his experiments, but I'm using Magnesium because it reacts a little faster with the acid.
This time, we'll collect the gas by allowing it to bubble up through some soapy water.

As the gas is produced, it passes through the tube into the soapy water and it's trapped inside the tiny bubbles which form. This gas is not like oxygen which supports fire, it's actually flammable. In 1783, it was named "hydrogen".
Now the oxygen needed for the fire to burn comes from above the bubbles. However, if we bubble hydrogen and oxygen into the detergent together so that the hydrogen and oxygen are right next to each other, the hydrogen burns even faster. Explosively in fact.





Here's another take.

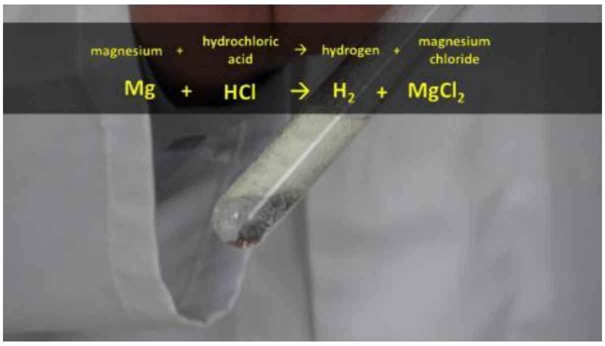
When we examine the video frame by frame, we can see the flash of light created by the burning hydrogen. What we don't see is any smoke, because when hydrogen burns the only product is steam, which eventually condenses to produce liquid water; pure, normal, everyday water.

To show you the water forming, we can also collect hydrogen gas in a dry upside down test tube and then ignite it. It's very hard to see, but the inside of the test tube is now a little misty because some of the water that was produced in the reaction has condensed on the glass.

Here's the video frame by frame. The hydrogen burned really quickly, producing a small flash of light and a popping sound.

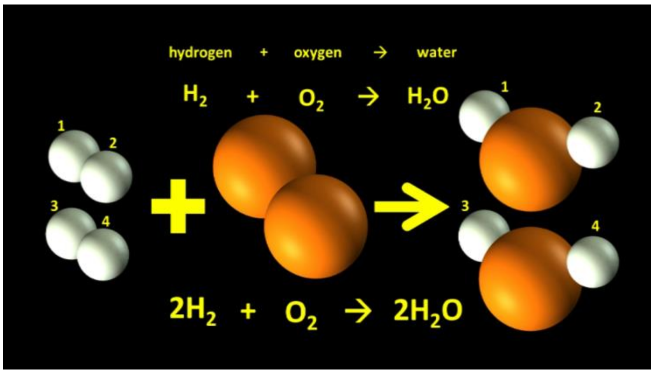
The word hydrogen in fact comes from the ancient Greek words "hydro" meaning water and "gen", meaning generator or producer. Hydrogen generates water when it burns.

magnesium + hydrochloric acid → hydrogen + magnesium chloride
$Mg + HCl \rightarrow H_2 + MgCl_2$



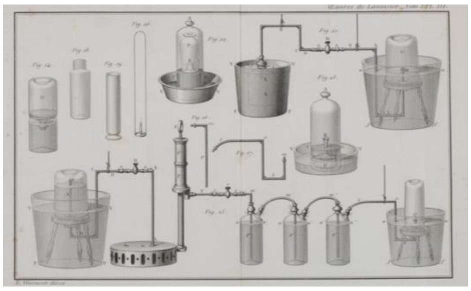
The chemical equation for the reaction that produced the hydrogen gas can be written as magnesium + hydrochloric acid produces hydrogen + magnesium chloride (which, once again, we couldn't see because it remained dissolved in the acid). In symbols we can write Mg + HCl produces H_2 (the hydrogen atoms in hydrogen gas always come in pairs) + $MgCl_2$.
This equation is unbalanced, because while HCl is made of 1 H atom and 1 Cl atom, the products on the right show 2 H atoms and 2 Cl atoms. To balance the equation we need to put a 2 in front of the HCl.

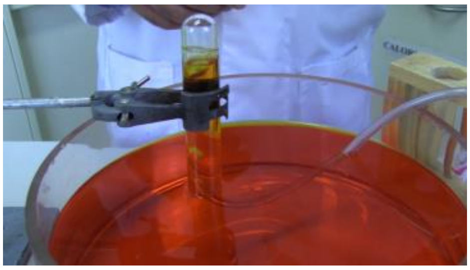
The chemical equation for hydrogen burning is: hydrogen + oxygen produces water. $H_2 + O_2$ produces H_2O. hydrogen + oxygen → water $H_2 + O_2 \rightarrow H_2O$



This equation is also unbalanced. One of our original oxygen atoms seems to have disappeared. In fact 2 H_2O molecules form for every 1 pair of oxygen atoms. Now though, we have 4 hydrogen atoms on the right hand side, so we need another pair of hydrogen atoms on the left hand side to react.
The balanced chemical equation can therefore be written as $2H_2 + O_2 \rightarrow 2H_2O$.

Now when performing their experiments in the late 1700s, they didn't use bubbles to trap gases. Their discoveries were made possible by the use of high-quality apparatus that could, for example, trap gases, weigh them really accurately, and then pump the gases into different containers where they could undergo further chemical reactions.



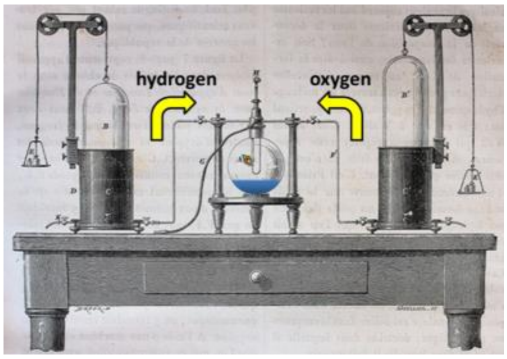


Just to demonstrate, if I fill a test tube with water (I've put some food dye into the water so that you can see it better) and then hold the test tube upside down in the water, the air pressure keeps the water in the test tube. I can now produce some hydrogen gas and bubble it up into the test tube.

The test tube slowly fills up, fills up that is with hydrogen gas.

Of course, they often used larger gas-trapping containers in many of their experiments.
After about 15 seconds, the test tube is full and can't hold any more gas.
I can leave the gas there for as long as I like or I can trap the gas in the test tube using a rubber stopper.

As expected, the hydrogen burns if I bring a lit match up close and a small amount of water has formed on the inside of the test tube since water is produced when hydrogen burns.



Henry Cavendish, the discoverer of hydrogen, had noticed that water forms when hydrogen burns, but, in the late 1770s, it was Antoine Lavoisier who worked out why. Lavoisier had a brilliant laboratory and a brilliant mind and he has been called the Father of Modern Chemistry for his discoveries.
In one experiment, he very slowly pumped pure hydrogen gas and pure oxygen gas into a glass vessel together, and allowed the hydrogen to burn as the two gases were pumped in. He ended up collecting about 20 millilitres of pure water, proving that hydrogen, when it burns, chemically reacts with oxygen to produce water.

So more or less at the same time that they figured out that air can't be an element, because it's actually a mixture of lots of different gases, they realized that water can't be an element either, because it's made of hydrogen gas and oxygen gas which have chemically combined together.

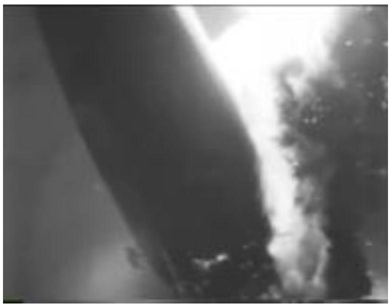
Now the thing to remember about chemical reactions is that the substance or substances that are produced have absolutely nothing in common with the chemicals that reacted in the first place.

Water, which we now know is made of hydrogen atoms and oxygen atoms, is a non-flammable liquid that freezes at 0°Celsius (32°F) and boils at 100°Celsius (212°F), but hydrogen is a flammable gas while oxygen is a gas that supports fire. They only turn to liquid when you cool them down to about minus 200°Celsius (about -300°F). Hydrogen and oxygen have nothing at all in common with water, even though water is made of hydrogen atoms and oxygen atoms.
Actual Boiling Points: O_2: -182.95°C (-297.31°F); H_2: -252.87 °C (-423°F)

So it bears repeating: when a chemical reaction takes place, the substances produced have nothing in common with the substances that originally reacted.

In a chemical reaction, atoms rearrange themselves and completely new chemicals form with different melting points and boiling points, different densities, different chemical behaviour, different everything.

Getting back to hydrogen, it was quickly realized that hydrogen gas is a lot lighter than ordinary air. A little over 100 years after it was discovered, they started using it in airships. This one, the German-built Hindenburg was about 250 metres long. However, because hydrogen is so flammable, it's quite dangerous. In 1937, it caught fire as it arrived in the United States, killing 37 people. This disaster effectively ended the use of hydrogen gas in airships. The smoke isn't coming from the burning hydrogen since burning hydrogen doesn't produce any, but from the burning fabric and other materials that the airship is made of.



Modern airships use another gas called helium, which doesn't burn. In fact helium gas doesn't chemically react at all, with anything!

Now the importance of hydrogen gas did not disappear after the Hindenburg disaster.
In the 1960s, rocket engineers started using hydrogen gas as rocket fuel. NASA's Space Shuttles, which flew 135 missions between 1980 and 2011, had three main engines which used hydrogen gas stored in the external fuel tank as their fuel. Oxygen gas, also stored in the external fuel tank but in a separate container, was also injected into the engines to allow the hydrogen to burn.

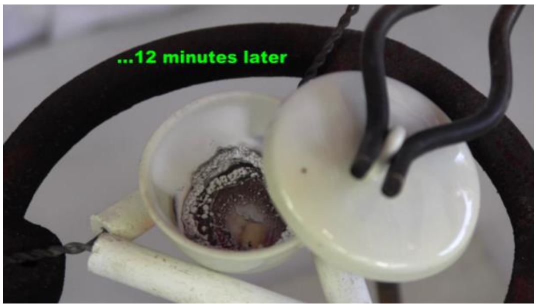
The hydrogen burns very cleanly producing steam, so it's difficult to see the exhaust. The solid rocket boosters on each side used another fuel which produced a fair bit of smoke.

While the so-called solid rocket boosters produced lots of smoke because they used a different fuel, the hydrogen burning in the three main engines burned very cleanly producing only steam so it's difficult to see the exhaust.

Part C: Nitrogen and the Atmosphere

So, in the late 1700s, it was clear that the air all around us wasn't, as the ancient Greeks thought, some pure substance which was one of the basic building blocks or elements of matter. Air was actually a mixture of lots of different gases.

In 1779, Lavoisier performed an experiment which showed that the air in our atmosphere is made up of about 20% oxygen gas and about 80% of another gas called nitrogen.
He slowly heated mercury metal in an enclosed container for quite a few days and the mercury slowly turned to ash.
This is what the mercury ash looked like. It's actually mercury oxide, HgO.
Because we now know that Mercury is poisonous I'll do a similar experiment with Magnesium.

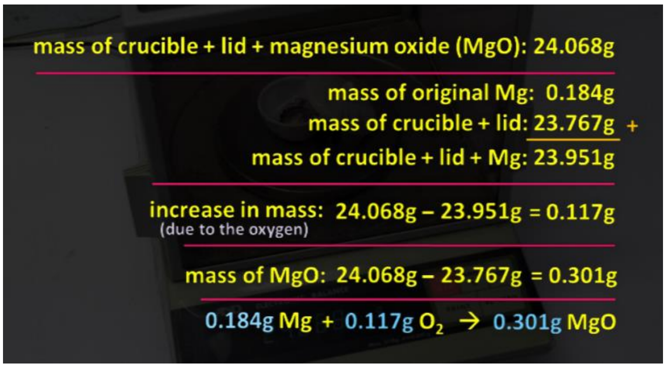


This strip of magnesium has a mass of 0.184grams, the crucible and lid have a mass of 23.767 grams and the combined total is 23.951 grams. If we heat the magnesium in the crucible, it eventually starts to burn. By placing the lid on the crucible, we can slow the burning process and limit the amount of smoke that escapes. The magnesium metal eventually turns into a whitish powder, which is called magnesium oxide, because the magnesium atoms and oxygen atoms from the air have joined together.

The chemical equation for the reaction is magnesium + oxygen → magnesium oxide.
$Mg + O_2 \rightarrow MgO$
Now there's 1 Mg atom on the left and 1 Mg atom on the right, so the Magnesium atoms are balanced. However, we started with 2 Os, so in fact we make 2MgOs. We need to put a 2 in front of the MgO so that the Os are balanced. Now we have 2 Mgs on the right, so we have to put a 2 in front of the Mg, and our equation is balanced.
If we now reweigh the crucible, its lid and the magnesium oxide we find that the combined mass has increased to 24.068 grams.

Let's now display all of our data, including the mass of the original piece of Magnesium, the mass of the crucible and its lid and the combined mass of these three things, and do a few calculations to make sense of all these numbers.

The overall mass has increased from 23.951g to 24.068g. The increase in mass, which we can easily calculate equals 0.117 grams. This increase in mass has come from all the oxygen atoms that have joined onto the original magnesium atoms.



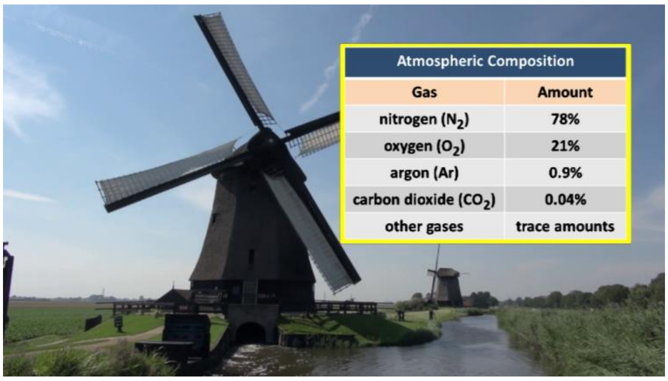
The mass of the MgO must be equal to our final mass, 24.068g, minus the mass of the crucible and its lid, which was 23.767g. This equals 0.301g.

So, 0.184 grams of magnesium combined with 0.117 grams of oxygen to produce 0.301grams of magnesium oxide. After this experiment, the air had ever so slightly less oxygen in it!

Now Lavoisier didn't know about atoms, but he noticed in his experiment, which, unlike mine, was completely enclosed so that nothing could get in or out, that once the mercury ash had formed, there was 20% less air in the container than had been there originally. He could tell because the drop in pressure in the container made the water level rise.
Some of the air had chemically combined with the mercury to form the ash.

Lavoisier pumped the remaining 80% of the air into an enclosed container which had some mice in it. He discovered that the mice could not survive in the gas so he named the gas azote [pronounced azert] which in Greek means "no life". In English we now call the gas "nitrogen".

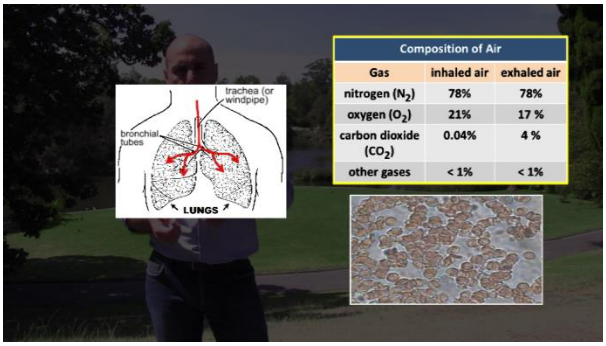
He then took the mercury ash and heated it really strongly in another enclosed container.
The ash, which as I said was mercury oxide, turned back into mercury metal and a gas. Mice placed into this gas could survive as normal because the gas was in fact pure oxygen.
(Now I should point out that most, if not all, oxides, like magnesium oxide and zinc oxide, don't break apart into the metal and oxygen when heated. Mercury oxide is one of the very few, that does.)



We now know that nitrogen gas makes up 78% of the atmosphere, oxygen 21%, another gas called argon 0.9%, and carbon dioxide 0.04%, while other gases exist only in trace amounts.

Now these figures are for dry air. Water vapour is also a part our atmosphere, typically about 1% of it, but this figure can vary from 0% to about 4% depending on the conditions.

Lavoisier later turned his attention to respiration. He designed masks and other equipment which allowed to him to measure the amount and composition of the air we breathe in and out.
He found that the nitrogen we breathe in, which makes up 78% of the air, all simply gets exhaled back out again.
However, though the air we breathe in contains about 21% oxygen and practically no carbon dioxide, the air we breathe out contains about 17% oxygen and about 4% carbon dioxide. We now also know that argon and tiny amounts of other gases are breathed in and out as well.

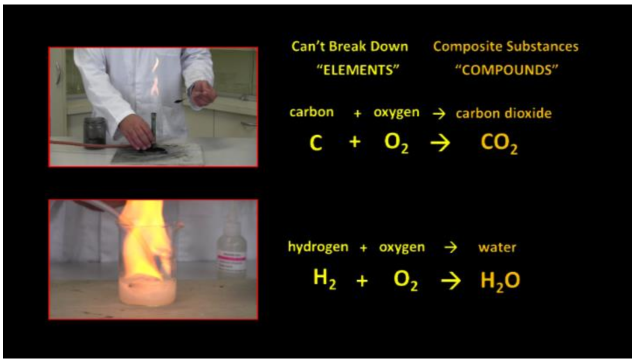


Despite not being able to achieve the accuracy of these figures, which have been obtained with modern equipment, Lavoisier nevertheless realized that some of the oxygen that enters our bodies is used up in chemical reactions with the food we eat, food being our fuel.
We now know that about one fifth of the oxygen we breathe in actually enters the blood stream from the lungs. The blood carries the oxygen to our cells where it chemically reacts with carbohydrates and fats to release the energy stored in them, energy we need to do all the things that we do.
The main chemical reaction can be written as
glucose + oxygen → carbon dioxide + water
The glucose, which is our main fuel source, is produced by the body by digesting the carbohydrates in our food.
The waste CO_2 is carried by the blood back to the lungs and we breathe it out. Heat is also generated as a result of these chemical reactions.

We sometimes say things like our bodies "burn" the food we eat. Of course there are no flames in our bodies, but what happens inside our bodies is a little similar to the process of burning flammable gases or wood, because when these fuels burn, they also chemically react with oxygen, generate heat and produce carbon dioxide.

Part D: Breaking it Down

Now what became clear to Lavoisier as he conducted all his experiments was the fact that some substances could not be broken down into simpler substances, and some of them could.



They knew that when carbon burned, whatever it was made of, remember they didn't know about atoms yet, combined with whatever oxygen was made of to produce something completely different: carbon dioxide. And whenever hydrogen burned, it combined with oxygen to form something completely different as well: water. Water and carbon dioxide were therefore composite substances, that is, they were each made of two different substances that had chemically joined together. We now call these types of substances compounds.

However, oxygen, hydrogen, and carbon were not made of anything else, and they could not be broken down chemically into other simpler substances. These things Lavoisier said were true elements, because they weren't made of anything else.

Once everybody realized that through carefully controlled experiments and accurate measurements they could work out which substances were elements and which ones were compounds, it wasn't long before atoms themselves were discovered so it's the discovery of atoms that we'll be looking at in our next episode. See you then.

Credits:
Written, directed and presented by Spiro Liacos.

Thanks to NASA for the Space Shuttle vision and the Apollo Stage Separation vision (which are public domain).