

Chemistry: Challenges and Solutions
Unit 1: Matter and the Rise of Atomic Theory
The Art of the Meticulous
Hosted by Christopher Morse

[Tease]

It takes just over 100 elements to make the entire known universe: from our morning breakfast, to our commute to school or work, and even for our entertainment. Combining elements to improve our world is at the heart of what it means to be human.

MICHAL MEYER: Chemistry is something that we are and also something that we do. Humans are unique in the sense that we do chemistry. We deliberately manipulate matter for our own purposes.

AHMED RAGAB: Where did chemistry start? It's a question that's almost impossible to answer because when you think about it chemistry is just part of our everyday life.

We all practice chemistry, usually without being aware of it. Our ancestors made cave drawings from animal fat, charcoal and even blood. We turn iron into steel, flour into bread, food into fuel, and water into electricity. There is almost no limit to the ways in which we transmute matter. Discovering, refining and combining new substances has evolved and grown into what it is for us today, the world we live in, a world of chemistry.

[Title: Unit 1 – Matter and the Rise of Atomic Theory]

CHRISTOPHER MORSE: Here we are at a beach. In the middle of this beautiful natural setting, chemistry probably isn't the first thing that comes to mind. Hi I'm Chris Morse and I'm a chemist, so why are we here at a beach? Because it's full of sand.

But I don't see sand. I actually see silicon dioxide. While that might sound scary, all it means is that there's one atom of silicon and two atoms of oxygen. And even the Ancient Romans could convert this into glass.

The sand on this beach can be separated with modern technologies into silicon and oxygen and that silicon can be converted into, computers, solar panels, and even my smart phone.

Nowadays, we would say that we live in a silicon age. Before that there was an iron age, a bronze age, a stone age. The one thing that's always been true is humans have named their periods of history after the chemistry they've been doing at the time. So over thousands of years chemistry has reached the point where we can take the sand on this beach and convert it into the chemical component that is the center of my cell phone.

[SEGMENT 1: The Origins of Chemistry]

While humans have practiced chemistry since the dawn of time, historians often trace the origins of chemical theory back to the 5th century BCE, when Greek philosophers started to think about what the world was made of. One theory put forward by Democritus claimed that all matter was composed of small, indivisible particles that he called “atomos.” While very different from our current view of the atom, Democritus’ “atomos” is the first instance of the idea of building blocks of matter.

An alternate theory introduced the concept of elements. Greek philosophers, including Aristotle, suggested that all matter was made of four elements: air, earth, fire, and water.

By the 9th century, these ideas reached the Arab world.

AHMED RAGAB: The very significant shift that happens at this period is the integration of all sciences from Greek origin, from Persian origin, from Indian origin together translated into one single language that people are using now to communicate their scientific knowledge.

One alchemist, Jabir, stands out because he combined Greek philosophy with his strong technical background.

AHMED RAGAB: What makes Jabir very significant is the type of training and career that he had. So he starts off as a practitioner, a son of a pharmacist and a chemist. He is very much aware of the simple processes needed in the market to produce compounds and materials that people need and use in their daily lives. And then he starts to learn new Greek philosophy and he starts to learn the theories about the making of the world.

And in his practice afterwards, he is able to combine both, to think about the theory and its implications. But also to consider the very practical concerns, such as tool making, such as the production of very useful materials that people can use in their lives.

Jabir is credited for discovering things like the sulfuric acid, like tartaric acid, like mercury even. What Jabir really did is to think about first how to purify them and this happened, for instance, through distillation. And he also tried to record what he perceived as very significant properties for these particular materials.

And then he was able to use many of them in the production of ink, of paper, of medications. And this shows us a move from the general view of everything is made of the four elements into a more practical view of that things differ based on very significant properties and therefore have a more systematized process of trying to change or to create something out of something else.

[SEGMENT 2: Separating the Beach]

CHRISTOPHER MORSE: All right. Here we are in a lab and I have this kind of gross beaker containing the sand, the salt water, the seaweed that I got at the beach. It's a mixture that I can now use some relatively simple techniques to help separate out.

The first thing I'm going to do, is pour this into this filter, which will allow us to separate out the solids up here in the top and the liquid should pour right through, essentially letting me separate out the solid from the liquid. However the salt water itself is still a mixture, and what I'd like to do is come over to here and show you where I took some salt water earlier today and I'm now boiling the salt water. Why would I want to do this? Well salt water – not a very good thing to drink.

What I'd like to do is to try and capture some of the water. But since the water is in the form of steam, I'm going to need something cool like this container of ice to help me get the steam vapors to re-condense back into liquid water. You can already see little droplets starting to form. I wouldn't necessarily want to drink these droplets of water since I'm in a lab and these containers might not be perfectly safe or clean.

So we have what is called a distillation apparatus. And it is actually boiling the water in that little round bottom flask, the steam begins to rise up and it turns the corner, and as it turns the corner it's colder over there and it condenses down and collects in that little flask over at the end.

Since the only thing more boring than watching water boil is watching paint dry we are actually going to speed up this portion so you can watch the separation of the salt from the water in this mixture. The nice thing about doing it this way is this is a very well designed system so we can purify all the water and have a nice clean water source at the other end.

So here in front of me we have the three different substances that we separated our beach into. Over here, we have the pure water now which we could drink, in the middle here we have the sea salt that we boiled the water away from, and sea salt is actually used as a fine cooking ingredient and here we have our sand, silicon Dioxide, which with modern techniques, I could separate out the oxygen leaving behind the element silicon, which has some amazing properties that can be used to solve the world's energy crisis.

[SEGMENT 3: Sand to Sun]

ETHAN GOOD: Silicon is an amazing material because you start with something as abundant as sand, and through a few simple processes, turn it into a device that can capture the sun's energy. When you're walking along the beach, all the little small pebbles of rock and gravel that you're stepping on is basically silicon dioxide, and what you really want from that is the silicon element that's contained in that oxide, and we're

able to strip that oxygen away from the silicon, which becomes the basis of our semiconductor.

The next stage of the process is using that extreme purity silicon, which we call polysilicon, and we bring it in here to Solar World and we melt it down into a liquid and begin to grow it back again in an extremely regular pattern called a crystal, similar to the way you would grow rock candy, or sugar crystals on a string.

MISCHA RAMSEY: So we are standing in the crystal growing hall at Solar World, which we like to call our silicon forest. We are ready to start the process of growing a crystal. If you're looking at the bowl you see the pure silicon, which is the silver rocks in the middle. The silicon is 99.9999% pure, or six nines, which means it's one part in a million that might be an impurity. In order to get the right electronic properties for silicon, what we do is we add an intentional impurity, which is called a dopant. In our case we add boron. The boron, you can actually see, are these little disc-shaped pieces in the middle of all of these rocks. This is not pure boron; it's actually silicon that's got boron in it at concentration that we need for the whole bowl. So what we're going to do is we're going to take all of the silicon and we're going to melt it, and then we're going to re-crystallize it in the shape that we want it to be in, in order to have a good solar cell down the line.

ETHAN GOOD: Chemically, there's really no difference between a polysilicon rock and a crystal. The difference is the actual placement of the atoms. Whereas the polysilicon rock is very random in its orientation, when you crystallize the material it's extremely ordered: each atom falls in a very specific place in space, and we use that order to make sure that we have very good ability to conduct electrons when we make our finished solar cell.

TONY CAYWOOD: Right now we have a furnace that's getting ready to melt down. It takes about three to four hours for the silicon to melt down to full liquid. We want to heat the crucible up evenly, so that's why we're rotating it around, and this silicon's starting to melt nice and slow.

Okay. Here we got one growing right now. This is further along in the process; it's about 80 millimeters in diameter. Diameters probably average about 206 millimeters. It's rotating and it's pulling at the same time. This process takes about up to two and a half days to grow, and if everything works out right you're going to have a perfect crystal.

MISCHA RAMSEY: So what we're looking at here is a single crystal of silicon. When I say single crystal, what it means is that all of the atoms are arranged in a nice, 3-D, orderly matrix. So when you're looking at this single crystal there's literally millions and millions and millions and millions of silicon atoms and every once in a while there's a boron atom. It's only one or two every ten million silicon atoms. But just that one or two boron atoms is enough to change the properties of this silicon and give it a net positive charge, so we can make a useful solar cell out of it.

ETHAN GOOD: So at this point when we've grown the perfect crystal that we've positively charged, we take that crystal and shape it into an ingot, which is a square shape, and then we start turning that square shape on it's side and cutting wafers. A wafer is an extremely thin piece of silicon: we're talking on the order of about 150 to 160 microns. That's thinner than the diameter of a human hair.

SOLAR WORLD WORKER: These ingots right here have just come out of the wire-saws. They've just finished being cut into wafers. So they're ingots no longer, they're wafers now.

ETHAN GOOD: So the next step in the process is creating a solar cell. A solar cell is essentially a battery. It has a positive side and a negative side. So in order to do that, we take the wafer, and we actually diffuse on one of the surfaces with a phosphorus gas. That phosphorus that incorporates just in the first few microns of the material creates a negative charge to the one surface, but the back of the wafer is still positive. What we've made now is a really thin battery, so that when light shines upon it, the positive carries in the device will actually get attracted to the negative portion of the solar cell. At this step in the process, we're putting the silicon nitrate coating on that helps us capture even more light that's hitting the surface of the solar cell. No, longer are we in Chemistry 101. This is some pretty advanced plasma chemistry going on here.

Throughout this entire process, we've started with a material that's extremely ubiquitous, sand, and we've turned it into a net to capture the sun's energy and turn it into electricity for us to use in a very clean and efficient manner every single day, from now until the next 50 years.

[SEGMENT 4: The History of Oxygen]

CHRISTOPHER MORSE: Sand is made of silicon and oxygen. And we have already seen that purified silicon can be used to make solar panels. But what about the oxygen? Like silicon, oxygen can stand on its own, or it can combine with other elements to make materials like sand or water, or it can be a component of the air around us.

By the end of the 18th century, Europeans had discovered that air was actually a substance that was a mixture of different gases.

And in the same manner that the alchemists had separated out solids or liquids into their different parts, they began to separate out the components of air.

MICHAL MEYER: Up until around the middle of the 18th century, air was considered to be just this one thing. Then in 1750, a chemist named Joseph Black discovered what we know today as carbon dioxide, but what he called 'fixed air'. So suddenly people realized air is not just air, air is made up of different things, different stuff, different gases. And if there's one gas, why aren't there more gases?

One substance incorrectly believed to be part of the air was called phlogiston. Phlogiston theory explained combustion. When a log burned, or a metal rusted, it

released a substance called phlogiston into the surrounding air until all that remained was ash or powder.

MICHAL MEYER: Now this was a good theory because it explained quite well what people saw in burning and rusting. By about 1770 it was pretty well accepted as a theory. So if you're thinking in terms of gases and in terms of burning and air, you're going to be thinking in terms of phlogiston theory.

French chemical philosopher Antoine Lavoisier was skeptical of phlogiston theory, especially after learning of an experiment with rusted mercury.

MICHAL MEYER: Many metals rust including mercury. And in the 18th century, they called that compound rusted mercury, they called it mercury calx. It's this red, kind of powdery looking stuff. According to phlogiston theory, if say I have mercury, and to use modern language I will say oxidize the mercury, then the rusted mercury, it should weighed exactly the same as the metal mercury. Now, a colleague of Lavoisier did some careful weight measurements and found this wasn't true. The mercury calx was heavier than the metal mercury. And this was completely wrong according to phlogiston theory. So something is going on that phlogiston is just not explaining.

How could something gain weight when it lost phlogiston? Lavoisier recognized the absurdity of this result, and had the tools necessary to disprove the phlogiston theory.

MICHAL MEYER: So, Lavoisier, when he learns of this experiment, he goes, "Ah-ha! I can kill phlogiston at last!" I'm exaggerating; Lavoisier would never have said that, but in effect that is what happened. And what is so great about Lavoisier, he doesn't just say, "Oh, this theory is wrong, end of story", he says, "This theory is wrong, I have a better theory. I can replace the phlogiston theory with my oxygen theory."

Lavoisier re-created the mercury calx experiments. He carefully weighed the metal, the calx, and the surrounding air. Based on his results, Lavoisier concluded that the rusted mercury was heavier because it interacted with a gas in the air, which he named Oxygen. This agreed with the principle of the conservation of matter that had been theorized, but had never been proven. Lavoisier measured away phlogiston theory.

MICHAL MEYER: People talk about the conservation of matter. Now, that had been more or less implicit in chemistry for a long time: the idea that matter is not created or destroyed. But unless you have really good instruments, you can't prove this, you can't show this. Lavoisier had very good instruments. He probably had the best chemical equipment of anybody in the world at that time, certainly the most sophisticated.

Through a series of carefully constructed experiments, Lavoisier pushed gas chemistry further. He isolated the elements oxygen, nitrogen, and hydrogen. Eventually, Lavoisier proved that water was actually a compound of two gases.

MICHAL MEYER: Lavoisier was one of the people who showed that water is a compound made of hydrogen and oxygen, and he would do demonstrations to show people these. So you would take two volumes of hydrogen and one volume of oxygen, and you would burn them together, and you would create this tiny, tiny, little bit of water. So a lot of gas and tiny amounts of water, for people watching, this was spectacular. I mean, for us, it's nothing; we know – hydrogen and oxygen, put them together, burn them, you get water. But at the time, it was something that you wouldn't have expected. Two gases forming a liquid like this, and forming such a common liquid, water. It was something very new, and something quite wonderful to learn about the world.

[SEGMENT 5: DEMO – Making Water the Hard Way]

DANIEL ROSENBERG: BOOM! Okay, now we're going to do an experiment to make water; a dangerous, loud experiment. And we're going to fill a balloon with one part oxygen and two parts hydrogen. So now we have one part oxygen and two parts hydrogen in this balloon, but we don't have water yet. In order to make water we have to react the hydrogen and the oxygen together. When I add the heat of a candle flame, the hydrogen and the oxygen are in intimate contact and are going to react almost instantaneously. An almost instantaneous reaction is an explosion. So I am going to put on these safety hearing protection and... don't even need to blow it out. The water that we produced from the balloon went away as steam. Lavoisier did a much more careful and gentle experiment. He made water from hydrogen and oxygen and was actually able to collect it and prove that the two to one ratio was, in fact, correct.

[SEGMENT 6: Atomic Manipulation]

CHRISTOPHER MORSE: A large part of the history of chemistry has been purifying materials and figuring out what elements they are made out of. However, by this point in time we've already discovered all of the stable elements in our world. So how do we make materials for the future? We need to combine these elements together in novel ways. And the properties of these materials depend on the arrangements of those elements on the atomic level.

TONIO BUONASSISI: The amount of solar energy reaching the surface of the earth in two hours is more than sufficient to power all of our energy needs for an entire year. There is more than enough solar energy out there. We just have to find better ways of capturing it. And we do that by manipulating the materials around us.

At MIT, Tonio Buonassisi and his team are working to make solar cells more efficient.

TONIO BUONASSISI: Silicon is a special material, because when light comes down, and it excites an electron, it allows it to move around the material. These electrons that are excited by sunlight are extracted from the device toward the metal lines, and these metal lines are connected to other metal lines that eventually lead into the electrical

lines in your house. In an ideal world, all of the electrons excited by light would be collected, but in the real world, some of those electrons that are excited don't make it to the contact metal, these are losses inside of a solar cell device.

So, imagine you're an electron inside of the solar cell material, and you're moving along happily, until you encounter an iron atom. And like a roadblock, it impedes your progress and stops you in your tracks. We don't want those iron atoms there, because they decrease the performance of the solar cell; they reduce the collected current. We want to get those iron atoms out of there. So what we're doing here now is we're hunting these defects; these very minute concentration. So we need specialized tools, but also specialized processes.

JOSEPH SULLIVAN: So, in my hand over here is a silicon wafer. If we were to zoom in on this and magnify its crystal structure by 10^{23} , we would see this. Where these individual balls are our silicon atoms. The clear rods are valence electrons. In our silicon solar cell we want it to be mostly silicon and the elements that we put in there. Now, in the manufacturing and refining process, it turns out the metal impurities are really good at moving around in between these little crevices, in between atoms, and creating problems in our finished solar cell device. So, an impact could be a very highly efficient silicon solar cell. It could be in the neighborhood of 24 percent efficient. Where one that is heavily metal contaminated could be around 10 percent.

One in a trillion atoms can disrupt the performance of this entire device. However, we have tools and techniques that allow us to get rid of these bad effects of those one in a trillion atoms. And that's a process that my colleagues in this lab have mastered.

ASHLEY MORISHIGE: So this machine is called a phosphorous diffusion furnace. The input to the furnace is just a material like this, a bare silicon wafer that's been chemically cleaned. We flow a mixture of nitrogen, oxygen and phosphorous at different times and at different temperatures across this wafer. During the phosphorous diffusion process, we are actually moving iron atoms from the bulk or sort of the center of the material out to the surface of the material, where the phosphorous is being diffused in. We are actually manipulating iron on the atomic scale.

JOSEPH SULLIVAN: So what we do to measure the efficiency of a solar cell is put it under simulated sunlight. So we have a lamp. We have some filters on it that make it look like the sun. And to measure the efficiency, what we will do is apply a voltage and measure a current. And we measure it at different voltages and different currents and that gives us what we call a current-voltage plot. And that can tell us a lot about the characteristics of our solar cell and, primarily, the efficiency.

TONIO BUONASSISI: So the first devices coming out of Bell Laboratories in the 1950's were on the order of six percent efficient. Nowadays, commercial solar cell devices are on the order of 16 to 17 percent efficient, typically. Solar energy today is on the cusp of being cost-competitive against fossil fuels. And therefore an increase of solar cell

performance from, say, 16 percent to 20 percent could revolutionize the adoption of that technology.

And so that's what drives our research group, you see. That is the goal that drives all of us, that unites all of us. We use atomic scale manipulation of material to improve performance and ultimately bring solar power to cost effectiveness over a wide range of markets in the United States. So we go from the laboratory, from hunting particles that are only a fraction of the diameter of the size of your hair, toward changing a macroscopic, a countrywide energy production system.

[WRAP-UP]

CHRISTOPHER MORSE: We're in a never-ending quest to sort of manipulate the matter in the world around us. The sand on this beach is made of a mixture of different elements. The silicon in the sand is the second most abundant element on the earth's crust and if manipulated properly can become the core of our modern chemical technology. Chemistry over thousands of years has developed to the point where we can change and control our chemical environment at this level.

[END]