THE WORLD OF CHEMISTRY

Program #4

MODELING THE UNSEEN

Producer Doug Bolin

Air Script: October 31, 1988

PRODUCED BY

EDUCATIONAL FILM CENTER
and
THE UNIVERSITY OF MARYLAND

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Computer graphics, chemists at work, drugs, volcanos

NARRATOR (MUSIC and NAT SOUND under):
A riddle. If chemistry is a science in search of facts, why is imagination so important? The answer is wrapped in mysteries. Why are there enormous volcanos of liquid sulfur on this distant planet? How do drugs work inside our bodies? And what explains the behavior of gases at different pressures? Chemists must probe events which cannot be observed directly. So imagination is the first step towards modeling the unseen.

SUPER: MODELING THE UNSEEN

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in art gallery

ROALD HOFFMANN (SYNC):
I'm in one of my absolutely favorite places, the East Wing of the National Gallery in Washington. Let's take a look at some sculptures. Here is this marvelous sculpture by Alberto Giacometti, a seated woman, less elongated than his usual representations. You know, no doubt Giacometti used a clay model in constructing this bronze figure, and, in another sense of the word "model," this sculpture, all art, gives us a representation of the essence of some expression of an emotion of some response to a piece of the natural world around. The artist is trying to understand that world. Chemists also want to understand the world that we live in, and in order to do that, we have to form hypotheses and models. The models that we use are different from those that artists have -- for instance, different from this beautiful sculpture by Isamu Noguchi. Chemists are often trying to observe things that we cannot see or touch directly.

MONTAGE: Gases, coal on conveyor belt, computer graphics and models, chemists at work in lab, microscope shots, volcanos

NARRATOR (MUSIC and NAT SOUND under):
Some things are too complex to study directly. A gas consists of billions of tiny particles. There are too many of them to observe all at once. So models are used to predict their behavior. Some processes happen too slowly. The geochemical events that produced this coal took place over millions of years. Some things are too far away to study firsthand. The chemistry on these outer planets can only be guessed through long range and indirect observations. Even when we can observe events close up, we may still need models to understand the chemistry that produced them. From the chemistry of the largest bodies in our universe to the behavior of particles so small they are invisible, chemists use models to imagine, then test explanations. They need models because these events are like black boxes that can't be opened. How do scientists make models to reveal such inner mysteries? To unlock these secrets, series demonstrator Don Showalter went to a class of sixth graders.

DS in classroom
with students

DON SHOWALTER (SYNC):
We're here to solve a problem for you today. Many times in chemistry, what we are studying we really can't see very well. In fact, we might not be able to see at all. So what we want to do, a little bit of an experiment with you today, and the experiment involves these two boxes. What we want to do is find out what's inside these boxes. All right. The box is locked so that we can't see inside the box. Now, what we want you to do is form in your mind a model. Do you know what a model is?

STUDENTS (SYNC):
Yes.

DON SHOWALTER (SYNC):
What is a model? A model, sort of the idea -- not a model like a model airplane, but maybe a model of a mental picture, huh? What could you do to be able to tell what's inside the box? How about if I pass it around. And now, what I want you to do is to form a mental picture in your mind of what's inside that box? What do you notice about the two boxes, in comparison? All right. One's heavy, one is light. All right. What else? What about --

CHILD (VO):
One makes sound and one doesn't.

DON SHOWALTER (SYNC):
Good. Say it real loud.

CHILD (VO):
One makes sound and one doesn't.

DON SHOWALTER (SYNC):
You betcha. One makes sound and one doesn't. Have you got a mental picture yet? What's inside? What's inside the light one?

CHILD (SYNC):
I don't know. It's either big or else there's nothing in there.

DON SHOWALTER (SYNC):
Anyone else?

CHILD (SYNC):
I think there's nothing because, when you shake it, you don't hear anything. And it's light.

DON SHOWALTER (VO):
So using your ears, huh?

CHILD (SYNC):
I think that there's like sponge or something soft in the box, because when you shake it, you don't hear anything, but the box feels heavier than if it were empty.

DON SHOWALTER (SYNC):
Okay. All right. Now, I want you to hold on to that idea for a minute. All right. Now we want to hear about the heavy box over here, hear the heavy people over here, huh? All right now.

CHILD (SYNC):
I think there's change in the box because when you shake it, you hear like chains going against the box, and it's heavy.

DON SHOWALTER (SYNC):
You hear what kind of a sound?

CHILD (VO):
Clanking.

DON SHOWALTER (SYNC):
Like a rattling or a clank, clanking sort of a sound in there, huh? And what else about the box.

CHILD (VO):
It's real heavy.

DON SHOWALTER (SYNC):
It's heavy. It's heavy, so there's something in there that is dense. Do you know what that word means, dense? Okay. Anyone else wanna give us an idea about the heavy box?

CHILD (SYNC):
I think there's just any kind of metal in there, because the noise it makes.

DON SHOWALTER (SYNC):
Any way we could look inside things without actually opening them up?

CHILD (SYNC):
We could X-ray the box to check what's in there.

DON SHOWALTER (VO):
All right. We've done that. Do you want to see them?

CHILD (VO):
The heavy one.

DON SHOWALTER (SYNC):
That's the heavy one. What do you see in there?

STUDENTS (VO):
Nuts, bolts, screws.

DON SHOWALTER (SYNC):
All right. Boy, we were close, weren't we? You were right on. You were thinking that it had all that metal in there, and certainly the X-ray shows it up. So we could study that box without even opening it up. Okay. What do you see in here?

STUDENTS (VO):
Nothing.

DON SHOWALTER (SYNC):
All right. So we say nothing in that box, huh?

CHILD (SYNC):
Right.

DON SHOWALTER (VO):
Everybody agree?

STUDENTS (SYNC):
Yes.

DON SHOWALTER (VO):
All right. Everybody in agreement, hold their hand up? All right. Let's open these boxes up and see what's inside there, huh? All right. Now, this one. Do you feel confident that this has nuts and bolts in it?

STUDENTS (VO):
Yes.

DON SHOWALTER (SYNC):
You're right on. You're right on. Look what's inside that box.

CHILD (VO):
Nuts and bolts.

DON SHOWALTER (SYNC):
Nuts and bolts, huh? All rightee. How about this box? What do we say?

STUDENTS (VO):
Nothing.

DON SHOWALTER (SYNC):
Nothing inside there.

CHILD (VO):
Possibility.

DON SHOWALTER (SYNC):
Possibility of having nothing inside. Here we go. All right.

STUDENTS (SYNC):
Cotton balls!

DON SHOWALTER (VO):
Cotton balls.

(NAT SOUND: Clapping)

MONTAGE: Freeze frames of students and DS

NARRATOR (MUSIC under):
The steps a scientist follows to develop a model are along the same path traced by the students. First, scientists make general observations about a situation and closely observe the behavior of the system being studied. (cont.)

NARRATOR cont:Then, relating these observations to their past experience, scientists try to imagine what model could explain their observations. Like the students, they build the model based on their past experience and their ongoing observation. Next, scientists must test their models. The students tested their models by examining X-rays of the two boxes. These tests are designed to confirm or disprove the model. One procedure, the X-ray test, supported a model that was false. When the box that looked empty was opened, it contained cotton balls. So scientists test their models using many different procedures. How does this method work in the real world? Let's start with a model of something on a very large scale.

Computer graphics of space and the solar system, observatory, telescope

NARRATOR (MUSIC under):
For centuries, scientists have been studying this kind of black box, our solar system. Until recently, these observations were limited to what could be seen through telescopes. We have had to rely heavily on models to explain the chemistry of these enormous bodies. One of these models concerned Io, the first moon of Jupiter. (cont.)

NARRATOR cont:
Dr. Torrence Johnson is director of the Voyager Project.

INTERVIEW: Dr. Torrence Johnson, Director, Voyager Project, JPL

SUPER: Torrence Johnson

DR. TORRENCE JOHNSON (SYNC):
Before we got the spacecraft out to the Jovian system, basically what we knew about Io was how big it was, how much it weighed, and how bright it was, to first order. How big it was and how much it weighed made it look just like the Earth's moon. So you started all of our modeling assumptions in the early days, before Voyager started, with the idea that Io was gonna be basically like the moon. There was one problem. It was about ten times brighter than the moon, in terms of its surface reflectance.

View of Earth from space, volcanos, lava flow

NARRATOR (MUSIC and NAT SOUND under):
Why was Io so bright? One model proposed that, unlike our moon, Io had once been covered with great amounts of water, volcanic activity had caused the water to evaporate, leaving behind a bright layer of salt deposits.

INTERVIEW: Dr. Torrence Johnson cont.

DR. TORRENCE JOHNSON (SYNC):
But, because it was the same size as the moon, we thought that all of this heating activity had occurred three to four billion years in the past, just as the moons had. So we thought it was dead. Our model was of a dead lunar interior with a salty outside probably blasted full of craters by meteorites.

Rocket launch, animated graphics of satellite

NARRATOR (MUSIC and NAT SOUND under):
In 1977, the first Voyager probe was launched to gather observations on Jupiter and Io from close range. Scientists waited for 18 months as Voyager made its lonely pilgrimage. The wait was worth it.

INTERVIEW: Dr. Torrence Johnson cont.

DR. TORRENCE JOHNSON (SYNC/VO):
What Voyager found, of course, was fantastically exciting. It found a body that's more volcanically active than any object we've ever seen in the solar system. (cont.)

Slides of Io

DR. TORRENCE JOHNSON cont:
The surface is covered with huge volcanic features, large collapse pits, calderas, volcanic flows, and most exciting of all, we caught several active volcanic eruptions in the process of going on, with Voyager I, throwing plumes of debris up a hundred to three hundred kilometers above the surface.

Computer graphics of Io, volcanos, geysers

NARRATOR (MUSIC and NAT SOUND under):
What could be the source of the energy for these volcanos? Investigators propose the following model: Io hangs in space between Jupiter at one end and Europa at the other. The gravitational force from each body tugs on Io, causing it to flex and heat up, as represented here in exaggerated form. So, in this model, gravitational energy generates the heat for the volcanism. But there was still something strange about the chemistry of these volcanos. They weren't volcanic eruptions like the ones here on Earth, with lava exploding or flowing out of the ground. Instead, they resulted from the same conditions that produced geysers, such as the ones in Yellowstone Park.

INTERVIEW: Dr. Torrence Johnson cont.

DR. TORRENCE JOHNSON (SYNC):
But they weren't water. We knew there wasn't any water now on Io, with respect to a spectroscopic evidence of that, so they proposed that the working fluid in this model was liquid sulfur or liquid sulfur dioxide, which can exist in liquid state fairly -- at fairly shallow depths below Io's crust.

GRAPHIC: Io differentiation

NARRATOR (MUSIC under):
But this raised another enigma. How did sulfur compounds instead of silicate rocks come to be the dominant lava on Io's surface? A new model arose. It proposed that, long ago, silicate rock sank to the interior of Io. Water evaporated from the surface. Sulfur compounds were the lightest materials not to boil away. They ended up as the dominant lava. Is this the final model of Io's sulfur plumes?

INTERVIEW: Dr. Torrence Johnson cont.

DR. TORRENCE JOHNSON (SYNC):
Well, when you build a model like this, you shouldn't get to thinking that the model represents reality. It will always change. In fact, we're not doing our job right if it doesn't change. It will always evolve as we get more information and revise our methods of observation based on the models.

RH in observatory	
	ROALD HOFFMANN (SYNC): The chemical processes on Io are vast in scale, and Io is very far away. A lot of chemistry involves an intellectual excursion in another direction, to the very small. Take, for instance, a gas. We can measure its volume, its temperature, its pressure. But what is really happening inside a gas?
Chemists working in lab	
	NARRATOR (MUSIC under): In order to understand, predict, and control what is happening inside a gas, we use a model called the kinetic particle model of gases. It assumes that a gas consists of large numbers of extremely small particles. There are billions of these particles in one breath of air. Let's make some observations and see how this model explains them.
DS in lab	
	DON SHOWALTER (SYNC): This apparatus that we have here will allow us to measure the pressure of a gas. Now, what we want to study now in our model here is several different variables: pressure, volume, and the amount of gas. One thing we're not going to vary is the temperature. We're gonna hold that constant. The temperature of the room now remains the same. (cont.)

DON SHOWALTER cont:
Okay. Let's do an experiment. What I want to do is add an amount of gas to this already trapped volume of gas in here. As I do, of course, you know that's going to increase the pressure. Right? I'm gonna add some helium. Look at the pressure. I'm doubling the pressure. Once it's up there, I'll shut that off. Now, what I have done is double the pressure of the gas. Now, what do you think that means in terms of the amount of gas added? I bet you said it doubled the amount of gas, huh? That's the intuitive guess. And you're right. If we double the amount of gas, we double the pressure. Now, we want our model to be able to explain that.

GRAPHIC: Gas particles and pressure

NARRATOR (MUSIC under):
This is a representation of the container we used in our experiment with a vast number of gas particles already in it. The particles are moving chaotically in all directions and colliding with the walls of the container. For the purposes of our model, suppose that we could make the gas particles enormously larger and see them in slow motion. And to make things even clearer, we'll focus in on the behavior of just a few particles. (cont.)

NARRATOR cont:
As these particles collide with the walls of the container, the many tiny collisions exert a force on the walls. The force exerted on each unit of area of wall is the pressure of the gas, shown here on this gauge. What would happen if we doubled the number of the particles in the container? There are now twice as many collisions per second against the wall. What does this do to the pressure of the gas? It will double it, because the number of collisions in a given unit area is directly related to the pressure of the gas. The more collisions in a given unit of area, the higher the pressure.

DS in lab

DON SHOWALTER (SYNC):
Let's do a second experiment now. This time we're going to vary the volume and the pressure, again leaving temperature constant. Now what I'm gonna do is release the piston and see if it can come up to this mark here which refers to double of the volume. As we release the piston, it comes up to double the volume, and look what happened to the pressure. The pressure now is half of what it was. It was on 2, and now it's back down to just a little bit below 1. It's down to about what it was originally. So we have doubled the volume and, in the process, the pressure was cut in half. (cont.)

DON SHOWALTER cont:
That's another observation that we've had. So we've done two experiments now involving the amount of gas and the pressure. In the second experiment now, we looked at the volume that the gas takes up, the volume of the container, and the pressure of the gas. Let's see how our model can explain these observations.

GRAPHIC: Gas particles and change in pressure

NARRATOR (MUSIC under):
What happens to the pressure if the volume of the container is doubled, but the amount of gas particles is kept the same? As the volume of the container increases, the gas particles have more room to bounce around. They are now striking the wall only half as often as before. The pressure also drops back to half of what it was at the smaller volume of our gas.

MONTAGE: Geysers, hot springs, clouds, , kinetic particle model graphic, computer graphic model, chemists working in labs

NARRATOR (MUSIC and NAT SOUND under):
The kinetic particle model applies to any gas under standard conditions. However, in the real world, there are many different types of gases, and the particles of one gas are different from the particles of other gases. Yet, even though they are different, all groups of gas particles obey the general rules laid out in the kinetic particle model. This is true regardless of the type of gas particles. The kinetic particle model deals with the average behavior of large numbers of gas particles. It doesn't deal with the shape of single gas particles. But in other areas of chemistry, models of the actual shapes of single particles are very important. What you are looking at now is a model of a drug compound used to treat ulcers. These models have opened the door to an unseen world inside our bodies, a world where drug particles interact with cells on a submicroscopic invisible level. They have led to remarkable discoveries in the fields of biochemistry and drug research. (cont.)

NARRATOR cont:
Dr. David Pensak and a team at Du Pont are one of several groups creating computer models of particle structure. How are these models used in drug research?

INTERVIEW: Dr. David Pensak, The DuPont Company

SUPER: David Pensak

DR. DAVID PENSAK (SYNC/VO):
Computers are very nice tools to help us better understand how nature puts her building blocks together to create the substances which we encounter in our daily life.

Animated computer models

What you are looking at now is a computer graphics picture of DNA, the thread of life. What we're trying to understand, in any kind of a model,

INTERVIEW: Dr. David Pensak cont.

is exactly what's going on at the level whereby nature is doing whatever it is, is happening. We cannot get down

Animated computer models

small enough physically to see that. So what we have to do is try to simulate this. The problem is that these particles are so small (cont.)

INTERVIEW: Dr. David Pensak cont.

DR. DAVID PENSAK cont:
that, by and large, chemists who never really had the chance to create a mental picture of what they're like, so what we have to do is develop models to enable them to think about things that are too small for them to actually look at.

Animated computer models

NARRATOR:
The key and lock model is an example. Picture a drug as a key. The cells in our bodies each contain many different kinds of locks. One of these locks, if opened, could result in a desired effect. But to open the lock, the key must be an exact fit. Computer models help researchers imagine the properly shaped particle.

INTERVIEW: Dr. David Pensak cont.

DR. DAVID PENSAK (SYNC/VO):
The problem that we have is, yes, you have a key, and yes, it fits into a lock. We have to worry about how does the lock and the key actually find each other, because they're both swimming around inside the body. There has to be some process of recognition whereby the key knows, "This is the lock I want to interact with." And we call the process by which it approaches the lock, the docking problem. (cont.)

Animated computer models

DR. DAVID PENSAK cont:
We're trying to simulate it on the computer, very much the same as worrying about how a boat pulls up to a dock, how to recognize where the appropriate slip is. But what makes this different than the boat docking problem is that we have a very oddly shaped slip -- the hole in the lock, if you will -- and we have to make sure we put just the right key in there.

INTERVIEW: Dr. David Pensak cont.

Because if the key that we put in doesn't fit, you don't get the desired activity at all. And if we have a key that can fit into multiple locks, you begin to have a side effects problem.

MONTAGE: Bottles on assembly line, chemists working in labs, computer models, pill

NARRATOR (MUSIC under):
To create a new drug, researchers may need to synthesize hundreds of compounds and test each. It is expensive and time-consuming. Models streamline the process by identifying which particles have the highest potential for success. And because these models help researchers to see substances in new and different ways, they sometimes yield unexpected breakthroughs.

INTERVIEW: Dr. David Pensak cont.

DR. DAVID PENSAK (SYNC):
Let me tell a little story that's near and dear to my heart. For awhile we had two computer graphic systems side by side, and one of my people was working on developing a new class of weed killers, another one was working on a class of molecules which were involved in treating of cancer, truly a high priority item. As luck would have it, they were both working, and they both got telephone calls at the same moment. They went back to their laboratories. When they came back, they inadvertently got on each other's terminal. And about 15 seconds later the first one yelled out, "What are you working on my class of compounds for?" He said, "I'm not." He said, "Yes, this is my compound over here." What came out of this was there was a similarity between the weed killer and the anticancer drug that had never been recognized before. Because the way we had been used to drawing these structures on a sheet of paper, is in a stylized representation which is really almost artificial, and you would have never seen that similarity. But when you display them exactly as nature is really dealing with them, there was a striking similarity. (cont.)

DR. DAVID PENSAK cont:
We wound up submitting some of our weed killers to the National Cancer Institute for screening, and it turns up they've got really significant antitumor activity. But who in their right mind would have ever thought of even taking a weed killer and dreaming that it would have any kind of activity in dealing with cancer?

SUPER: MODELING THE UNSEEN

MONTAGE: Volcanos, clouds, chemists working in labs, computer models, program graphics, pills

NARRATOR (MUSIC under):
To review: We use models to understand events and processes that we cannot see or touch directly. To develop a model, the scientist starts with observations. These observations are used to form a mental representation, a model of the process being studied. Then the model must be tested. One important chemical model is the kinetic particle model of gases. It states that gases are composed of billions of submicroscopic particles in constant random motion. Models explain processes that vary from a very large scale to a very small scale, from the macro level to the micro level. (cont.)

NARRATOR cont:
They are used to understand the chemistry on the surface of distant planets, such as the massive sulfur volcanos on Io. And they are also used to predict the behavior of infinitesimally small drug particles inside our bodies. For the chemist, models are a crucial tool for understanding the unseen.

RH in an art gallery with chemical models

ROALD HOFFMANN (SYNC):
It turns out that I am actually very much a model builder. I want to tell you a little story about a piece of work. Actually, it was the work that won the Nobel prize for me and for Kenichi Fukui of Japan in 1981, and that involved building models. There is an important class of organic reactions in which a chain is converted into a ring. Now, that looks like a rather simple process. It turns out to be actually a very important one in the chemistry of Vitamin D. But when you look in detail at this process, all kinds of richnesses emerge. For instance, in the process of forming that ring, the two ends of the chain can rotate together, like this, so that the red lines are on one side of the ring. Or, alternatively, they can rotate in another way, and now you see that the red lines are on opposite sides of the ring. (cont.)

ROALD HOFFMANN cont:
Now, those are two different molecules, and the remarkable thing, and crucial for the chemistry of these molecules, is that one or the other of these rotations, not both, are followed, depending on the number of carbon atoms in the chain. Fukui and I were able to construct a model, using methods of physics, to explain this preference. That model, within a very short period, was tested by the experiments of many people around the world. I wish I could tell you that every model that I have built has been as successful as this one. Some have been, and some haven't. Enough have been right to keep me going.

Credits, Closing Montage, Closing Music

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THE WORLD OF CHEMISTRY

Program #5

A MATTER OF STATE

Producer Doug Bolin

Air Script: October 31, 1988

PRODUCED BY

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<u>THE WORLD OF CHEMISTRY</u>

Program #5: A Matter of State
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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: The natural world

NARRATOR (MUSIC and NAT SOUND under):
There is a mystery to this world around us, an idea so obvious we take it for granted, but so important that all chemistry starts from it. Everything in our world exists in one of three states, as a gas, a liquid, or a solid, but can change from one state to another. How is this possible? What happens as a solid becomes a liquid and a liquid a gas? In the world of chemistry, it's all a matter of state.

SUPER: A MATTER OF STATE

<u>THE WORLD OF CHEMISTRY</u> OPEN: Montage, Music, Logo

RH next to Potomac River

ROALD HOFFMANN (SYNC):
The Great Falls of the Potomac River, near Washington. Everything in the scene around me, the rocks, the flowing water, the trees on the other side, even the air that I breathe, everything is matter, it's chemical. And even though we see hundreds of different substances, millions were I to look with a microscope, these substances fall into certain groups or classes that we can identify as gases, liquids, and solids. These are the states of matter. Gases are tenuous, compressible. The space that matter fills -- we call that volume -- is obviously occupied less densely in gases than it is in the other states of matter. Liquids are fluid, deformable, more dense than gases. And solids are more compact still, often denser. And it's not only that the states are there. We, or nature, can change them.

MONTAGE: Shots of crystals, lava, streams, balloons, clouds

NARRATOR (MUSIC and NAT SOUND under):
Why is a crystal like an iceberg? How is lava like a stream? What does a balloon have in common with the air around it? The iceberg and the crystal are both in the solid state. (cont.)

NARRATOR cont:
This lava and the water in the stream are both in the liquid state. The matter inside this balloon and the air around it are both in the gaseous state. Under certain conditions, matter changes state. What makes this transformation possible? Water at one temperature is a liquid, at another temperature a gas, at still another, it is a solid. If we are to begin unraveling the secret of matter's transformation, temperature is a clue. What is its effect on liquids and gases?

DS in lab

DON SHOWALTER (SYNC):
Let's start out by looking at the effect temperature has on pressure. What I'm going to do is heat this pan. This is a rigid pan, has some water in the bottom of it. Now, as the water is heated, it will change state. You're very familiar with the term steam, huh? Steam, now, is gaseous water. Now, as that steam is formed from that liquid, liquid to gas, it will drive out the air that was inside that can, and, hopefully, we'll be able to see some of the steam that is coming out of the top of the can. Once we have driven all the air out, what I'm going to do is put the top on there, and we'll let the can cool and see what happens with the pressure as the temperature decreases. What do you think? (cont.)

DON SHOWALTER cont:
Do you think there's enough steam coming out of there to indicate that the, all the air has been driven out? We'll take the burner off, turn that off, we'll cap this up. All right. Now, as the temperature decreases, the can cools, that steam will change back into liquid. As it does that, it will decrease the pressure inside the can. Oh, do you hear that? As the pressure decreases, what, anything happen out here? The atmospheric pressure didn't change. It's pushing on the can just like it was before, but since the pressure is less, as we decrease the temperature the pressure decreases, the can starts to cave in. There it goes. Now look at the can. Notice how the can is crushing. The reason now, again, is because of that atmospheric pressure, the gas of the atmosphere. Inside now, the pressure was reduced because the steam condensed into that liquid, leaving a decreased pressure inside. The atmospheric pressure pushed in the can.

MONTAGE: shots of steam, natural geysers

NARRATOR (NAT SOUND under):
So heating a liquid can change its state to a gas, and there appears to be a relationship between the pressure of matter in the gaseous state and its temperature. But what is the nature of this relationship?

DS in lab

DON SHOWALTER (SYNC):
We'll use this apparatus to try to understand that relationship between the temperature and the pressure of a gas. We have a rigid container here. This is a steel ball that is attached to this pressure gauge. Now, because it's rigid, the amount of gas inside and the volume of the gas will remain the same. The only things we'll vary are pressure and temperature. Let's try it and see what happens. All right. We'll heat it up, using this burner. So as we increase the temperature of the gas inside the ball, what happens to the pressure? Can you see that pressure, what's happening there? It's increasing, isn't it, the number is getting higher? So, as we increase the temperature of a gas, we also increase the pressure. Alright. Now, what would happen if we take the heat away and cool it? Let's see. I'll take the burner away and we'll turn off the gas, and we'll let it cool. It's not cooling fast enough. Let me help it. I've got this ice water bath. I'll stick the ice water bath up there, and we'll cool the ball, and look what happens now to the pressure. As the temperature decreases, the pressure of a gas also decreases. So we see the relationship between the temperature and the pressure of a gas.

Close ups of equipment from DS demonstration

NARRATOR (NAT SOUND under):
What is happening to the submicroscopic particles of a gas as they are heated and cooled? How does this affect pressure?

GRAPHIC: Kinetic energy of particles

NARRATOR (MUSIC under):
If we could slow down the gas particles and focus on just a few of them, they would look like this, far apart, moving randomly, in straight lines. When they collide with the walls of the container, they exert a pressure against the walls. These moving particles possess kinetic energy. Their speed depends on their temperature. As the gas is heated and the particles move faster, they collide with the walls of the container more frequently. Because they are moving at greater speed, they also strike the walls with greater force. Both effects, the greater number of collisions and the greater force of the collisions, contribute to the increase in the pressure of the gas when the temperature is increased. Cooling a gas decreases the speed of the particles. As the temperature is decreased, the kinetic energy of the particles decreases. They slow down. They strike the walls less frequently and with less force. As we cool a gas down to a certain point, we continue to decrease its pressure.

Close up of lab demo

NARRATOR (NAT SOUND under):
But if we cool a gas beyond that point, something dramatic happens.

Clouds, lightning, rain

NARRATOR (MUSIC and NAT SOUND under):
The gas changes state, to become a liquid. The fact that gaseous matter becomes liquid matter at a low enough temperature is important to us. Every year we use billions of liters of different gases.

MONTAGE: Hospital shots, soft drink factory assembly line, scuba divers, computer chips, oil platform

NARRATOR (MUSIC and NAT SOUND under):
In hospitals, pure oxygen helps very ill patients breathe more easily. In soft drink factories, another gas, carbon dioxide, gives beverages their fizz. Just plain air, a mixture of mostly nitrogen and oxygen, is bottled under high pressure for scuba divers to breathe underwater. Gases are also used in the manufacture of integrated circuits, the processing of steel, the recovery of oil, and many other places.

People cooking with gas,
LNG trucks

NARRATOR (MUSIC and NAT SOUND under):
But the place we are probably most familiar with is the home, where we heat and cook with a gas called methane or natural gas. And we would have a hard time using natural gas if we couldn't liquefy it at low enough temperatures. Lynwood Bazemore is Chief of Baltimore Gas and Electric's Liquid Natural Gas Facility.

INTERVIEW: Lynwood Bazemore, Chief of Baltimore Gas and Electric's Liquid Natural Gas Facility

SUPER: Lynwood Bazemore

LYNWOOD BAZEMORE (SYNC):
The primary reason for liquefying natural gas is to give us added storage capacity. Capabilities of storing LNG are much greater as a liquid than as a gas. To demonstrate, methane, liquefied, is reduced in volume over 600 times. We liquefy during the summer, when our system demands are low. That gas is made available then for storage. And in the winter months, when the demand is high, we can supplement our supplies with our own LNG.

LNG plant

NARRATOR (MUSIC and NAT SOUND under):
Natural gas is converted to a liquid and stored at plants like this throughout the world. Liquefaction is a three-step process. The gas comes in through pipelines in a gaseous state. But it contains impurities, like water vapor and carbon dioxide. So the first step is to cool the gas enough to freeze out the water vapor. This is done in towers that are filled with coils of a cold liquid similar to antifreeze. As the natural gas passes over them, water vapor condenses and forms ice. The natural gas then goes to a filter system that removes other impurities. Now the gas is ready to be chilled to a liquid.

INTERVIEW: Lynwood Bazemore (cont.)

LYNWOOD BAZEMORE (SYNC):
The liquefaction process simply reduces molecular motion. That provides for the condensing of the material. When we remove the sensible and latent heat from the methane from 60 degrees Fahrenheit down to minus-260, molecular motion is essentially slowed down.

LNG plant

NARRATOR (MUSIC and NAT SOUND under):
The red tanks in this plant contain natural gas that is waiting to be liquefied. The white tanks contain liquefied natural gas. The volume occupied by natural gas in the liquid state is so reduced that one white tank can hold 125 red tanks.

INTERVIEW: Lynwood Bazemore (cont.)

LYNWOOD BAZEMORE (SYNC):
We store LNG in essentially what is just a large Thermos bottle. The tanks are not refrigerated in any way other than the other refrigeration supplied by the liquid within the tanks. The tanks are essentially a tank within a tank. They're insulated around a top and bottom, and there's no additional refrigeration needed. One of the benefits of liquefying natural gas is that it makes it essentially portable. Methane, or natural gas, in its natural state as a gas, must be delivered via connected pipeline from Point A to Point B. However, as a liquid, LNG can be delivered by a truck, rail, or even shipping.

Close up of flowers
being dipped in LNG

NARRATOR (MUSIC and NAT SOUND under):
Another advantage of a liquefied gas is its extremely low temperature. How cold is it?

DS in lab

DON SHOWALTER (SYNC):
In this container I have an element that we're all familiar with, but most of the time as a gas, nitrogen, only this is liquid nitrogen. In here, a couple racquet balls. Notice how they bounce very well. Now, what will happen to those balls as I put it in that liquid nitrogen? Now, this liquid nitrogen is at a temperature of minus-196 degrees Celsius. So the temperature inside there now is some 225 or so degrees below room temperature. So that ought to change the properties of those balls that are inside there quite a bit. Well I think the balls have been in there long enough now. Let's see what happens. I'll put these gloves on, because that liquid nitrogen is very cold. I don't want to burn my fingers. Alright, I am gonna take one ball out and I'll set it right here and let that one alone. And I'll take the other one out. And just to show you what this liquid nitrogen has done, because it is so very cold, I'm gonna take that ball and hit it with this hammer. Here we go. (cont.)

DON SHOWALTER cont:
The ball shatters. So we see now that there has been a tremendous change in the properties of that particular ball because of this low temperature. Alright now here's the other ball -- it's warmed up so now so that I don't need that glove anymore. Look it's back to normal. So this fast freezing process even with something as cold as liquid nitrogen really doesn't harm the material. It certainly changes the properties immediately like this ball that we shattered, but after a while when it warms up, it's back to normal.

Close up of flower being crushed

NARRATOR (NAT SOUND under):
Liquid nitrogen also has many practical uses.

MONTAGE: Packages of food

NARRATOR (MUSIC and NAT SOUND under):
We take fresh food at the grocery store for granted. Its delivery depends on trucks that use liquid nitrogen for refrigeration, cooling the food without freezing it. Other foods are packaged and flash-frozen using liquid nitrogen.

Chemist working
in lab

NARRATOR (MUSIC and NAT SOUND under):
And biochemical researchers continue to develop cryogenic techniques for freezing living tissue without damaging it. This work will make it possible to store whole organs for indefinite periods.

RH next to Potomac River

ROALD HOFFMANN (SYNC):
We see now how matter can change from a gas to a liquid. In the process, energy is admitted in the form of heat. Something has to be taken away, and this is why we cool a gas, in order to liquefy it. The reverse process is that of heating a liquid in order to make it go into the gaseous state. These energy changes are crucial, and they're also part of our everyday experience. For instance, we can understand now how it is that we cool off when we sweat or when someone puts a wet cloth on the brow of a feverish person. What happens is that water liquid evaporates, goes to water gas. In order to accomplish that, heat has to be supplied to the liquid water. That heat must come from somewhere. It comes from my skin. That is why my skin feels cooled off when I sweat.
(cont.)

ROALD HOFFMANN cont:
These energy changes that we have been discussing, in the observable macroscopic world of gases, liquids, and solids, must find their origin, their causes, in the microscopic world of atoms and molecules. Let's take a look at one particular substance as it moves through the three states of matter.

DS in lab

DON SHOWALTER (SYNC):
What you're looking at is a closed container of bromine. See the bromine liquid here, red, dark-brown liquid, and the bromine gas filling the rest of the vessel, a red-brown gas. I'm going to make use of this liquid nitrogen again. Remember, it's very cold, minus-196 degrees Celsius. To lower this vessel so that the finger in the vat gets into the liquid nitrogen. Now, what will happen if that temperature is, that bromine should change state, so the gas should go into the liquid, and the liquid should go into the solid. So we see all three phases, all three states of matter in action. Now, let's wait a little bit and see what happens now while that flask cools down. At this stage now we can see all three states of matter. This is the bromine gas, the top part up here. The dark material now is the bromine liquid, and at the very bottom is the yellow solid of bromine. All three states of matter. (cont.)

DON SHOWALTER cont:
We know that as we go from the gas and decrease the temperature, we go to a liquid, we decrease the temperature further, we go to the solid.

GRAPHIC: Kinetic energy and change of state

NARRATOR (MUSIC under):
On the submicroscopic level, the bromine particles in the gaseous state are moving quickly and chaotically. As the temperature decreases, the particles slow down until the attractive forces between them overcome the randomizing forces of kinetic energy. When these two forces reach a balance, the particles begin to stick together in clumps. When the clumps become large enough, gravity pulls them down to the bottom of the container. Now the particles are in relatively close contact. Attractive forces are holding them together, but they are still moving. As the liquid becomes colder, the particles lose even more kinetic energy. This results in another change of state. The liquid becomes a solid. Now the attractive forces hold the particles in a regular and ordered form that extends in three dimensions.

MONTAGE: Crystals

NARRATOR (MUSIC under):
Crystals are one of the most beautiful examples of this ordered arrangement of particles. Although they look like they were fashioned with a sculptor's skill, these formations are completely natural. They come from one of the most extensive collections of rare crystals in the world. Housed in the vaults of the Smithsonian Museum, many are too delicate for public display. What gives crystals their unique appearance? Dan Appleman is a geologist at the Smithsonian.

INTERVIEW: Dan Appleman, Smithsonian Geologist

SUPER: Dan Appleman

DAN APPLEMAN (SYNC):
A crystal is a particular kind of matter in which the chemical elements, which compose all kinds of matter, are very highly organized. They are not just organized, but they are organized into a very orderly array, like a column of soldiers. An extremely ordered form of matter is what we see when we look at a crystal. What this means is that, within a crystal, the chemical elements are arranged in a particular way to form a building block. Now, you can think of the building block as being like a, like a brick in a brick wall. (cont.)

DAN APPLEMAN cont:
And these building blocks within a crystal then are stacked in a very regular arrangement, in three dimensions, just like the bricks are stacked in a wall.

MONTAGE: Crystals

NARRATOR (MUSIC under):
And in crystals, unlike other forms of matter, you can sometimes see the shape of these submicroscopic building blocks with the naked eye. If the conditions are right, the external shape of the crystal is the same as the shape of the particles that make it up. Because of this, crystals provided one of the first clues to the fundamental nature of solid matter.

INTERVIEW: Dan Appleman (cont.)

DAN APPLEMAN (SYNC):
Way back in the 16th Century, the famous Danish naturalist, Nils Stenson, observed that wherever a crystal of quartz, such as this, was found, the angles between the faces were always the same. They weren't just random faces. They always had the same angles between them. And, in fact, quartz from anywhere in the world, from Hot Springs, Arkansas, like this huge slab, or from Brazil, like these beautiful amethysts, it doesn't matter where the quartz comes from, what color it is, what shape the crystals are, the angles between their faces are always the same.

MONTAGE: Crystals

NARRATOR (MUSIC under):
Infinitely repeating patterns of chemical elements, the invisible world of fundamental particles laid bare through the external beauty of these shapes. In crystals, we can also see how particles in a solid are arranged to create strength.

INTERVIEW: Dan Appleman (cont.)

DAN APPLEMAN (SYNC):
This is different from other forms of matter. For example, in a gas, the chemical elements are only very loosely and weakly organized, if at all, and they have very little relationship one to the other, which is why a gas can expand to fill any volume that one wishes. In a liquid, the chemical elements are a little bit more organized. There is an attraction between the elements, and so a liquid has a volume to it. But it will flow and fill any shape volume that you want to pour it into, because it does not have any rigidity at all. But it is more organized than a gas. A crystal is far more organized than a liquid. A crystal has a rigid shape which will not change, because the chemical elements that form the crystal have a rigid arrangement with respect to each other, which does not deviate.

MONTAGE: Crystals

NARRATOR (MUSIC under):
Strong and rigid, but elegant and fascinating, crystals take many forms. From gemstones like the Hope Diamond, the largest blue diamond known in existence to natural specimens of all shapes and colors, crystals exert a grip upon both our imagination and our scientific curiosity.

INTERVIEW: Dan Appleman (cont.)

DAN APPLEMAN (SYNC/VO):
I think the most fascinating thing about crystals, at least from the standpoint of a scientist that wants to study matter, is the unique insight that a crystal gives you into the nature of matter itself, into the way that chemical elements behave toward each other. It's very hard to do this in a form of matter such as a gas, or a liquid, where the chemical elements don't really have much to do with each other.

MONTAGE: Crystals

But in a crystal, the intimate association of the elements tells you a lot about the nature of the chemical elements themselves, just like an intimate association between people will tell you a lot about individuals. And so I find crystals especially fascinating because they tell us so much about the nature of the chemical elements themselves.

SUPER: A MATTER
OF STATE

MONTAGE: Nature shots, program graphics, program demonstrations, LNG plant, LNG trucks, crystals

NARRATOR (MUSIC under):
To review: Matter can occupy three different states: gas, liquid, and solid. Changes of state depend on the motion of submicroscopic particles. The motion of these particles depends on energy. Cooling particles takes away energy and slows them down. Heating particles adds energy and speeds them up. In a gas, these particles move quickly and randomly, they have no set volume or shape. In a liquid, the particles slow down and clump together. We use gases, such as natural gas, in many important ways. Cooling a gas into a liquid decreases its volume dramatically. This makes it possible to store and transport it more efficiently. In a solid, particles of matter have a definite volume and shape. They are held in a pattern that repeats itself in three dimensions. Crystals are a highly ordered form of solid matter. They were one of the first clues to the arrangement of particles in the solid state.

RH next to Potomac River

ROALD HOFFMANN (SYNC):
The states of matter are few, but the ways in which they are realized, the number of different substances around us, are many. Let me give you an example. I'm breathing oxygen, the life-giver, and that's obviously a gas. But here is another element, sulfur, that's chemically very closely related to oxygen, and yet it's obviously different, it's a solid at room temperature. Now, there are, obviously, different forces at work between the atoms or molecules of sulfur and oxygen within these two substances. We want to know why that is so. We have to probe deeper; we have to then ask what is the nature of the atom, what is it that makes an oxygen and a sulfur similar, or different? We will begin to look at this in the next program.

Credits, Closing Montage, Closing Music

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THE WORLD OF CHEMISTRY

Program #6

THE ATOM

Producer Doug Bolin

Air Script: October 31, 1988

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THE WORLD OF CHEMISTRY

Program #6: The Atom
Producer Doug Bolin
Air Script: October 31, 1988

Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Space and galaxy shots, scientist at work, atom graphic

NARRATOR (MUSIC under):
What is the ultimate nature of matter in our universe? Throughout recorded history, the human mind has pondered this question. What are the smallest chemical building blocks that make up our world? For hundreds of years, chemists proposed models of this invisible particle, and used them successfully. Yet only in the 1980s did humans finally see what had been predicted for so long, the atom.

SUPER: THE ATOM

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in museum

ROALD HOFFMANN (SYNC):
I'm in the New York Hall of Science, a lively hands-on science museum in Queens. This quartz crystal, crystals like this have been the object of admiration by people over thousands of years, and of use. Sand, small quartz crystals as in glass and cement, and quartz crystals themselves have been used in radio receivers. But you know, when I, as a scientist, looked at this quartz crystal, what I want to see is the source of all of this perfection. I want to look into its innards. Why do these planes meet at this specific angle? What makes it so transparent? I want to take this crystal apart. I want to take it into smaller and smaller pieces, to apply to it microscopes of increasing magnification. And I can do that. And when I go to a magnification of the order of a hundred million, I will see the indivisible component of this quartz: silicon and oxygen atoms. Actually, it wasn't as easy as I've made it out to be. It took us a good 2,000 years to get to see those atoms.

Shots of machinery

NARRATOR (MUSIC under):
Using devices that range from the massive and complex to the small and simple, we have unlocked the atom and studied its structure

Atomic bomb explosion

NARRATOR (MUSIC under and atomic bomb blast SFX):
And we have learned of the incredible power held within it.

Shots of microscope, scanning machine for human brain, computer analysis of human body

NARRATOR (MUSIC under):
Each day this knowledge of the atom is applied in many ways. In medicine, signals from the atom are analyzed to produce vivid images of the body that can eliminate exploratory surgery. We can even examine mental activity in the brain.

MONTAGE: Shots of nuclear power plant, auto plant, labs, metals, telephone wires, paints, farm worker, cosmetics, fabrics, plastics on conveyor belt

NARRATOR (MUSIC and NAT SOUND under):
Nuclear reactors generate electricity for our homes and industry. In chemistry, the atom is central. Through our knowledge, we can predict and control chemical reactions. We can develop new alloys of metals, altering their properties to make them harder or more malleable, increasing their electrical conductivity or manipulating their strength. (cont.)

NARRATOR cont:
And a new generation of ceramics, superconducting and extremely strong, has been born. Our understanding of the atom enables us to create new drugs and paints, fertilizers and insecticides, cosmetics and fabrics. With our modern knowledge of the atom, we have developed new materials, materials that have found their way into every aspect of our lives. Scientists use models of the atom constantly as they investigate the chemistry of the world around us. But where did the idea of the atom come from?

MONTAGE: Ancient Greek buildings, close ups of rain on branches

NARRATOR (NAT SOUND under):
It began with a Greek philosopher, Democritus. He proposed that all matter was made up of extremely tiny particles called atoms.

Close up of chemical reaction in beaker

NARRATOR (NAT SOUND under):
Much later, in the 1800s, scientists revised the idea of the atom to explain events like this. By then, chemists were establishing that specific chemical reactions involve the combination of definite amounts of starting materials. (cont.)

NARRATOR cont:
They also noted that, after the reaction was finished, the starting materials had yielded definite amounts of end products.

Archival photograph of John Dalton, close up of chemical reaction in beaker

NARRATOR (NAT SOUND under):
Chemists like John Dalton used the idea of atoms to explain this, proposing that during reactions, atoms combined in predictable ways. Dalton's ideas were the beginning of our modern model of the atom in chemistry.

GRAPHIC: The nucleus and the electron cloud

NARRATOR (MUSIC under):
In this model, the atom has three basic components and two basic regions. One of the components is called a proton and another, the neutron. Together, the protons and neutrons make up the first region of the atomic world, the nucleus. The number of protons is what determines the identity of the atom. Protons and neutrons are held together by incredibly strong forces in the nucleus, which is actually extremely small compared to the total size of the atom. For example, this is the nucleus of a relatively simple atom, helium. (cont.)

NARRATOR cont:
The other region of the atomic world is occupied by the third component, electrons. This fuzzy cloud represents the space around the nucleus occupied by the electrons, called the electron cloud. The number of electrons in the cloud is equal to the number of protons in the nucleus. The electron cloud is 10,000 times larger than the nucleus. These glistening dots represent some of the possible positions of helium's two electrons as they move about the nucleus. Exactly how do the electrons move? Where are they at any given moment? No one knows the details of the electrons' motion. What is known are the chances of finding it at any given point around the nucleus at a particular moment. Where the chances are high, the cloud is dark; where they are low, the cloud looks lighter. Using indirect methods, scientists have established that atoms are all basically like this modern model.

Shots of atom imaging instruments

NARRATOR (NAT SOUND under):
Throughout this century, scientists have imaged the atom with different x-ray techniques. Then in 1981 Gerd Binnig and Heinrich Rohrer of IBM in Switzerland invented a new microscope, producing brilliant images of single atoms.

INTERVIEW: Dr. Robert Hamers, Research Scientist at IBM

ROBERT HAMERS (SYNC):
Well the first time I saw atoms, it was about two or three o'clock in the morning. Of course, I was doing most of my work at night because the instrument itself is extremely sensitive to vibration, so most of our experiments are done at night or on weekends. And it was about two or three o'clock in the morning, and I was staring at this image, and I started to notice this regular pattern appearing, which I knew had to be the positions of the atoms, and it just got better and better, and I was just elated. Eventually, tears came to my eyes because I was so happy, having worked on this day and night for so long.

Dr. Hamers working with STM, close-up of STM

NARRATOR (MUSIC under):
Dr. Robert Hamers is at IBM's research division in Yorktown Heights. He has made significant contributions to the imaging capabilities of the Scanning Tunneling Microscope, STM for short.

INTERVIEW: Dr. Robert Hamers (cont.)

SUPER: Robert Hamers

ROBERT HAMERS (SYNC):
If you've been told ever since grade school science days that atoms are the ultimate building block of materials, now we can go in, we can actually look at those atoms, and so that's incredibly exciting to be able to do that.

MONTAGE: Images of the atom

NARRATOR (MUSIC under):
The STM can produce both and two and three dimensional images with color enhancement. Here each small cone is an atom of silicon. These spears are the atoms in gallium arsenide, a compound used in computer chips. And in this two-dimensional image, we see atoms of aluminum and silicon.

INTERVIEW: Dr. Robert Hamers (cont.)

ROBERT HAMERS (SYNC):
Our present day understanding of the atom is that it consists of a very small nucleus consisting of protons and neutrons, and this nucleus is surrounded by a diffused cloud of electrons. So with this Scanning Tunnelling Microscope, what we're doing is mapping up the contours of these electron clouds.

MONTAGE: Needle, images of the atom

NARRATOR (MUSIC under):
The STM uses an extremely small needle to trace the shape of each atom's electron cloud, producing images like this. Images of the tiniest particles of the elements in the world around us. Images of an idea that began over 2,000 years ago, images of the atom.

INTERVIEW: Dr. Robert Hamers (cont.)

ROBERT HAMERS (SYNC):
One of the unique features of the Scanning Tunnelling Microscope is that, in addition to being one of the few instruments which can actually be used to observe individual atoms, it's also relatively inexpensive and provides a wealth of information. I think it's very likely that within five or ten years, certainly every chemistry department in this country will probably have at least one Scanning Tunnelling Microscope.

MONTAGE: Images of the atom, archival photographs, atom graphic, close-up of chemical reactions in dishes

NARRATOR (MUSIC and NAT SOUND under):
The STM images were a dramatic confirmation of our modern view of the atom. (cont.)

NARRATOR cont:
But long before we could actually image individual atoms, a series of simple experiments had given us information about the components within the atoms. One of their most important characteristics is charge. Electrical charge holds the nucleus and the electron cloud together and determines the course of chemical reactions. How does electrical charge work in the atom? Series demonstrator, Don Showalter.

DS in lab

DON SHOWALTER (SYNC):
You notice anything different? Believe it or not, I did comb my hair this morning. What you're seeing is the result of electrical charge. This device now is producing an electrical charge that is being transmitted through my body to the hairs on my head. The electrical charge is what's making them stand on end. How is this happening?

DS in lab

DON SHOWALTER (SYNC):
What you see here are four ping-pong balls covered with foil. This is a glass rod. If you rub the rod with fur, it picks up a certain kind of charge, a positive one. Matter now can be charged in one of two ways. It can be charged positively or negatively. (cont.)

DON SHOWALTER cont:
And the type of charge is very important. Let me show you why. If I take this positively charged rod and pass it near these balls, the charge is transferred to the balls, and look what happened. They repel. The balls are both positively charged, and positively charged balls repel one another.

Close up of balls and rods demonstration

NARRATOR:
When a negative charge is applied to the balls, the same thing happens. The balls become negatively charged and repel each other.

DS in lab

DON SHOWALTER (SYNC):
Now, what would happen if I took that negatively charged ball and moved it close to this positively charged ball? Let's try it and see. As we move them close together, look at that, they attract one another. So negative charges attract positive charges; unlike charges attract; like charges repel. Now, that's an important concept to learn if we're going to understand the world of the atom.

GRAPHIC: The atom

NARRATOR (MUSIC under):
So positive and negative charges attract in the atom, holding the electron cloud to the nucleus. How did we find out which components were positive and negative?

Archival photographs of William Crookes, close up of Crookes tube

NARRATOR (MUSIC and NAT SOUND under):
An experimental device developed by William Crookes helped provide the answer. The Crookes Tube. It produces a glowing stream of electrons. By using magnetic and electric fields, scientists were able to deflect the electrons. With this procedure, they were able to show that the electrons were negatively charged.

GRAPHIC: The proton and neutron

NARRATOR (MUSIC under):
In a similar experiment, another particle was discovered. It had a positive charge and was christened the proton. Much later, in a different experiment, a particle with no charge was found and named the neutron.

Close up of Crookes Tube

NARRATOR (MUSIC and NAT SOUND under):
In every atom, equal numbers of positively charged protons and negatively charged electrons balance each other. So the overall charge of an atom is zero. The atom is neutral. But the question of how positive and negative particles were arranged in the atoms still needed resolution.

Archival photograph of Ernest Rutherford

NARRATOR:
The first clue came from an experiment performed by a physicist, Ernest Rutherford.

DS in lab

DON SHOWALTER (SYNC):
What you see here is a recreation of the Rutherford experiment. He used an element named polonium, which gives off positively charged particles. Now, he put the polonium into a lead box, something like this. It has a small opening in it. This is a lead barrier. It has a tiny hole in it that will allow only a thin beam of positively charged particles to pass through. There's an opening here, and then here is a very thin piece of gold foil. (cont.)

DON SHOWALTER cont:
Surrounding the gold foil is this ring, which is specially coated with a material such that when a positively charged particle hits it, it gives off a flash of light. Alright. Now, what do you think would happen if those positively charged particles hit the gold foil? Well, Rutherford thought they would pass right on through the foil and hit the ring about right here. Boy, was he in for a surprise! Now, here's what actually happened.

GRAPHIC: Rutherford's gold foil demonstration

NARRATOR (MUSIC under):
Most of the particles passed right through the foil and hit the screen behind it, but not all of them. A few were deflected sideways, and about one in every 20,000 of them bounced off the foil back towards the source. Rutherford was astonished.

Archival photograph of Ernest Rutherford

ERNEST RUTHERFORD (VO):
It was about as credible as if you'd fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

GRAPHIC: Rutherford's gold foil demonstration

NARRATOR (MUSIC under):
What was deflecting some of the particles? Rutherford calculated that each atom must have a nucleus, a center with a large mass and a positive charge concentrated into a small volume. The nucleus had to be massive enough to deflect the heavy particles bombarding it. And since the bombarding particles have a positive charge, the nucleus must have a positive charge to repel them. So once in awhile a particle would closely approach the nucleus and bounce back. But the majority of the particles passed right through the negatively charged electron cloud.

RH in museum

ROALD HOFFMANN (SYNC):
Rutherford's ingenious experiment gave us a simple model of the atom, the heavy nucleus with the positive charge and most of the mass, and around it like negative electrons. Then from quantum mechanics, another 20th Century development of physics, we got a picture of how the electrons move. That was a cloud, and it's represented here in the model. The electrons don't move in orbits like planets around the sun, but they do move. (cont.)

ROALD HOFFMANN cont:
Sometimes they are near the nucleus, sometimes they are far. And we can, on the average, determine where they are. The electrons, though small, are moving throughout the whole volume of the atom, and when two atoms come together -- that's actually what chemistry is all about, atoms coming together to give molecules -- it is the electrons that feel each other first, not the nuclei. This is why the chemist is so interested in electrons. They make the difference, ultimately, between carbon, hydrogen, or lead.

MONTAGE: Crystals, minerals, ores

NARRATOR (MUSIC under):
What is it about the electrons that makes all the atoms of one substance different from all the atoms of another substance? The basic substances in the world around us each have a different number of electrons in their atoms. These electrons move about the nucleus in patterns that are different for each type of atom.

GRAPHIC: S-clouds and p-clouds

NARRATOR (MUSIC under):
For example, we have already seen one way that electrons may move around an atom, forming a cloud that looks like this. Here is a different cloud, shaped like an hour glass. (cont.)

NARRATOR cont:
The spherically shaped cloud is called an s-cloud. The hour-glass shaped cloud is called a p-cloud. What is the difference between the s- and the p-cloud?

Close-up of image of atom

NARRATOR:
Energy. Each electron cloud has a certain amount of energy associated with it. This is called its energy state. The shape of the cloud depends on its energy state.

GRAPHIC: Energy levels

NARRATOR:
If we were to diagram the energy levels of the s- and the p-cloud, they would look like this. The p-cloud would be placed higher than the s-cloud because the electrons in it have a greater amount of energy.

Close-up of atom image

NARRATOR:
And if energy is added to the atom, it is possible for the electron to change from one cloud shape to another. As it reverts to its initial state, the atom gives off energy signals.

Chemist working in lab

NARRATOR (NAT SOUND under):
Chemists can use these signals from the electrons to distinguish between the atoms of many different substances, even when these atoms are present in very small numbers. How does this work? Environmental analysis is one example.

MONTAGE: Children playing

NARRATOR (NAT SOUND under):
In our environment, there are many trace elements. Some of them like selenium are harmful if too much is ingested but are essential to human health in small amounts.

MONTAGE: Chinese life: street scenes, researchers, ferry boat, food, soil, home life

NARRATOR (MUSIC and NAT SOUND under):
For example, thousands of people in a region of China once suffered from a disease of the heart muscle. In fact, many died from it. Researchers analyzed the residents' surroundings. Using techniques that detect the energy signals from the electrons of different elements, they tested their water, their food, their air and their soil, looking for something out of the ordinary. Finally, they identified an abnormality in the soil. (cont.)

NARRATOR cont:
It was lacking in selenium, a vital trace element. Crops grown in the soil were deficient in selenium, so there wasn't enough in the residents' diet. This led to the heart disease. But once the inhabitants started taking selenium supplements, the disease was greatly reduced.

Shots of chemists working in labs

NARRATOR (NAT SOUND under):
Environmental analysts also use signals from the atom to detect elements that are harmful even in very tiny amounts. Lead, for example.

MONTAGE: Urban street scenes, lead paint chips (removal and detection)

NARRATOR (MUSIC and NAT SOUND under):
Lead can enter our environment in many ways. Because it was used as a gasoline additive, lead was present in our atmosphere above normal levels. Much of this lead settled in the soil of urban areas, where some of it still remains. From the soil, small amounts of lead may work their way into our water supply, or our food. Our water may also pick it up from older pipes that were joined together with solder containing high amounts of lead. (cont.)

NARRATOR cont:
A most common source of lead poisoning is lead-based paint. Until a few years ago, most paint contained lead. If paint chips are accidentally ingested, their lead accumulates in the body. How do chemists use energy signals from the electrons to identify the atoms of substances like selenium and lead?

Chemist working in lab

NARRATOR (NAT SOUND under):
One technique is emission spectroscopy. Dr. Robert Watters is head of atomic spectroscopy at the National Bureau of Standards.

INTERVIEW: Dr. Robert Watters, Head of Atomic Spectroscopy, National Bureau of Standards

SUPER: Robert Watters

ROBERT WATTERS (SYNC):
Emission spectroscopy is an important part of analytical chemistry because it gives us the opportunity to find out what atoms are in a sample, and we can look at the possibility of a large number of different atoms being in the sample, and we can decide how much of each of these atoms are in a sample, pretty much all at the same time.

Shots of spectrums and a flame burning substances

NARRATOR (NAT SOUND under): The key to emission spectroscopy is color. When energy is added to an electron cloud, by heating it, for example, it gives off light that is a particular blend of colors. Each substance is different. Copper burns a bluish green; sodium, yellow; lithium burns red; barium is a pale green. These colors or wavelengths of light can be separated into a pattern called the spectrum. The spectrum for each particular kind of atom is different from that of every other atom.

INTERVIEW: Dr. Robert Watters cont.

ROBERT WATTERS (SYNC): Now the element lead has a specific set of energy levels, and the wavelength of light that is given off by electrons, excited electrons from a lead atom, would have a specific value, so that we could tell indeed we are looking at lead and not any other atom. And then the interesting thing, that is, that the number of lead atoms that are in this sample will cause a change in the intensity of this particular wavelength of light, namely, the more intense that wavelength is that we see, the greater the number of lead atoms in the particular drinking water sample that we were interested in.

Shots of a flame

NARRATOR (NAT SOUND under):
What happens to an electron when energy is added? How does it produce its unique spectrum?

GRAPHIC: Electrons in excited states

NARRATOR (MUSIC under):
Here is an electron in an s-cloud. Under normal circumstances, it maintains this energy level, neither gaining nor losing energy. This is called its ground state. When the electron in an s-cloud is exposed to energy from an external source -- for instance, when light is shown on it -- it may absorb energy and enter an excited state. If it absorbs an amount of energy exactly equal to the difference in energy between the two clouds, something unique occurs. The shape of the electron cloud changes from an s-shape to a p-shape. The electron has moved to a higher energy level. The change is instantaneous and complete. There are no stages in between the s-shape and the p-shape. But the electron tends to seek out the lowest energy level available, so once it absorbs energy and changes to the p-cloud, the electron emits the energy as a particular color of light. In the process, it goes back to the ground state, the s-cloud, a lower energy level. (cont.)

NARRATOR cont:
But as long as the energy source is present, the electron keeps flipping back and forth between the two cloud shapes. It keeps emitting the same pattern of color, the same energy signal each time it goes from an excited state back to its ground state.

INTERVIEW: Dr. Robert Watters cont.

ROBERT WATTERS (SYNC):
The energy difference is specific, in many cases, to a given atom. So that the light that is given off in the case of emission spectroscopy, the wavelength of light indicates what the energy difference was between the upper level and the lower level, and therefore, that wavelength or color of light gives us an indication as to what atom it was that we were looking at in the first place.

SUPER: THE ATOM

MONTAGE: Chemists working in labs, program graphics

NARRATOR (MUSIC under):
To review: Understanding the makeup of the atom is important to understanding chemistry. In our modern model, the atom has three components: positively charged protons, neutrons with no charge, and negatively charged electrons. (cont.)

NARRATOR cont:
The electrons occupy a space called the electron cloud. Different electron clouds have different shapes, depending upon their energy level. Two of the most common are the s-cloud and the p-cloud. When the s-cloud changes to a p-cloud, energy is absorbed. When the p-cloud changes to an s, energy is given off. Scientists can use a technique called emission spectroscopy to analyze these energy signals and identify what types of atoms are present.

RH in museum

ROALD HOFFMANN (SYNC):
In another exhibit at the Hall of Science, we see the many different colors emitted by atoms in lamps. In this program we've looked at the structure of the atom. We understand those marvelous electron clouds around the nucleus, and, in an image that you saw at the beginning of the program, produced by a technique called scanning tunneling microscopy, we actually showed you an atom. Chemistry, like any human enterprise, operates on many levels. With partial, incomplete understanding, it's sometimes wrong. Incredibly, it's most of the time right. (cont.)

ROALD HOFFMANN cont:
About 50 years before anyone ever knew about the atom, there was devised a remarkable chart summarizing all the properties of the atoms. That chart, called the periodic table, is the subject of our next program.

Credits, Closing Montage, Closing Music

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