The Story of the Atom

(aimed at middle-schoolers, fascinating for adults)

By Joy Hakim

I. The Ancients

The One Basic Thing

A long, long time ago, actually it was about 2,500 years ago—which was before Socrates, or Plato, or Aristotle, or any of the Greeks you may have heard about—there lived a man named Thales (THAY leez). He is said to be the world's first philosopher-scientist. The first to look for explanations in observed facts, not myths. The first scientist to leave his name on his ideas.

We don't know much about Thales as a person, except what others tell us. And they tell of a many-sided genius who was a lawgiver, a civil engineer (he changed the direction of the Halys river), an astronomer, a mathematician, and a teacher. It is said that he predicted the solar eclipse of May 28, 585 B.C., and that he figured the height of a pyramid by measuring its shadow, using the Sun's position to do it. Perhaps most important to people of his time, he worked out a way to tell distance at sea. For seafaring people, that was an enormous achievement.

Thales tried to discover a basic unit, or element of life. Water—which takes three forms (solid, liquid, gas)—seemed logical. It was a reasonable start for a search that continues today.

The world is full of differences, and yet, Thales had the idea that underneath all the complexity there is a plan—some call it a divine plan—that explains everything. He, and his followers in Greek-speaking Ionia (today, western Turkey), looked for answers in the world about them, not in mythology or wizardry.

Thales asked, "What is the nature of matter?" By that he meant: What are we made of? What is the world made of? Is there one thing that ties everything together?

Those questions are the big ones that scientists from his time until now have tried to answer. Is there something that is basic to all life? Keep reading and see if you can find the answer to that question.

"Earth, Air, Fire, and Water," says Empedocles

Thales said life's basic element is water. Another Ionian, Anaximedes, said it was air. Other Greeks said fire, or earth. Empedocles (em PED uh kleez), who lived in the fifth century B.C., said it was all four of those: earth, air, fire, and water.

That idea of four elements—earth, air, fire and water—was one of the longest lasting and most influential scientific hypotheses in all of world history. For centuries and centuries and centuries (more than 2,000 years) people believed it—although it would turn out to be wrong. Some children were still being taught about earth, air, fire, and water in 19th-century American schools.

Empedocles was wrong in the elements he chose, but right in his idea that, instead of a world where everything is different and unrelated, there are certain basic substances that combine to make up everything else. We now realize that earth, air, fire, and water aren't basic elements. We've found over 100 elements (we discovered some of them in high-technology lab experiments). It was the Ionians who got us searching in the right direction.

What's important to remember about all this is that the

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After many years as a teacher, reporter, and editor, Joy Hakim now writes nonfiction stories for children. She is completing a 6-volume history of science for middle-schoolers, from which this article is drawn. Her 10-volume set, A History of US, *which* American Educator *introduced with articles in 1990 and 1993, earned the Michener Prize In Writing and is now being adapted for a PBS series called "Freedom" that will air early next year. The science books should be published by fall 2003; as publication information becomes available, it will be posted on our Web site* ***(www.aft.org/publications/american_educator)****. For other information and how to become a test site, contact* ***byron@amerhistpub.com.*** *Special thanks to physicists John Hubisz, president of the American Association of Physics Teachers; Hans Christian von Baeyer, professor at the College of William and Mary; and Gerald Wheeler, executive director of the National Science Teachers Association, for their assistance.*

The Ionians had come up with those four basic elements. Democritus thought there must be something still smaller, something they all had in common.

Greeks trusted their brains, and they understood that to know the large (the universe), they must investigate the small (basic elements). That's exactly what science does today.

"Numbers," says Pythagoras

Pythagoras (puh THA guh russ) was born (in 582 B.C.) on a Greek island, Samos, which had a world-class prosperous port. When Pythagoras was a boy, ships carrying new ideas seemed to blow in on almost every breeze. Samos boasted engineering marvels: a tunnel with water pipes cut through a big hill, a manmade harbor, and the largest of all known Greek temples. But its greatest marvel would turn out to be Pythagoras himself. He tied philosophy to mathematics.

How do you make sense of the universe? Is it a messy place that takes on meaning as we slog through mountains of information—trying this, trying that—adding one block of knowledge to another? (Believe that and you're an Ionian-style scientist.)

Or, is it an orderly, perfect creation that can be understood through mathematical formulas and headwork? (Believe that and you're a Pythagorean.)

Actually, the modern scientific method combines both approaches—pure thinking along with observation and attempts to find proofs (through experimentation)—but it took a long time to get that method working.

For Pythagoras, the way to understand the universe was by searching for things that are absolutely true—and numbers seemed perfect for that quest. "All is number," he said. And he meant it. Everything in the world, he believed, could be explained through mathematics. He went still further; he believed numbers were divine, an expression of God's mind.

By plucking musical strings of different but carefully measured lengths with the same tension, he found that sounds have exact number relationships. That gave order to music that no one had imagined before. If music can be explained mathematically, why not other things?

He focused on the horizon; then he cut through that horizontal plane with a straight up and down vertical line and he had a right angle. Pythagoras must have played with right angles in his mind. He is identified with a theorem that seems simple to us now, but was an astonishing achievement: *The square of the hypotenuse (the longest side) of a right triangle equals the sum of the squares of the other two sides.* It's called the Pythagorean Theorem: $A^2 + B^2 = C^2$.

Some historians say the Babylonians knew that theorem before Pythagoras, but he understood its importance and introduced it to the Greek-speaking world. Whatever the historical truth, he usually gets the credit.

There is an exactness to the world, an orderliness, and it follows rules that can be proved with numbers—that's what Pythagoras told us, and it has been confirmed again and again.

Pythagoras believed that the universe has a mathematical base, and that its structure and relationships can be described with mathematical formulas. He made that a foundation of Western science. No one has done more.

"There's an 'atom,'" says Democritus

I would rather understand one cause than be King of Persia, said Democritus (duh MOK rih tus), who was born about a hundred years after Pythagoras. Now the King of Persia had about as much power as anyone could have—and he was fabulously wealthy, too—so only those who understood the power of ideas would get what Democritus was saying.

Democritus was born in Thrace, which was an unfashionable, out-of-the-way place for a philosopher. "What can you expect from someone born in Thrace?" people may have said. It was a country to the west of the Black Sea and north of the Aegean, and it was not a center of philosophy. But that never stopped powerful thinker Democritus.

Democritus believed that to understand the universe you need to know what it is made of. The Ionians had come up with those four basic elements: earth, air, fire, and water. Democritus thought there must be something still smaller, something that unified these "elements"—something they all had in common.

He said there had to be a smallest substance in the universe that can't be cut up or destroyed and is basic to everything else. He called that smallest substance an "atom" (from *A-tomos,* which means "unable to be cut"). "Nothing exists," said Democritus, but "atoms and the void." (By void, he meant empty space—nothingness.) The atoms that Democritus had in his mind were solid, hard, and compact. Nothing could penetrate them. They were in constant motion, and they were too small to be seen.

Much of what we know of Democritus is hearsay. Except for a few words, his writings have been lost. (In those days before printing, all books had to be hand-copied so there weren't many copies.)

Was he right? Is there a basic building block of life? A smallest of the small out of which comes everything? It's a question we're still considering.

But brains and imagination can only take you so far in science, and then you hit a wall. Without the technology to experiment and test things, you can't confirm your ideas. That was the problem the Greeks faced. There didn't seem to be any place to go with science. It was hopeless to look for atoms; if they existed, they were too small to be seen.

So the next generations headed in a different direction.

Socrates (SOCK ra teez—465? to 399 B.C.), who lived in Athens and was called the wisest man in the world by the

Oracle of Delphi, turned from physical science to a study of the human soul. "Know thyself," he told his followers, echoing the words of that oracle. This is good advice but it doesn't do much for scientific research.

Socrates never got interested in atoms. Neither did his famous student, Plato, or Plato's famous student, Aristotle. Aristotle was an organizer and a classifier and an all-around thinker with a mind few others have matched. But he rejected the idea of atoms. He thought that even those basic substances, called "elements," could be divided endlessly—and that you'd never get anything else. There is no bottom-line particle, said Aristotle. Forget atoms, he said. And, for centuries to come, most scientific thinkers did just what Aristotle told them to do.

II. The 'Atom' Idea Returns

Why Can You Compress Air Without Changing Its Weight?

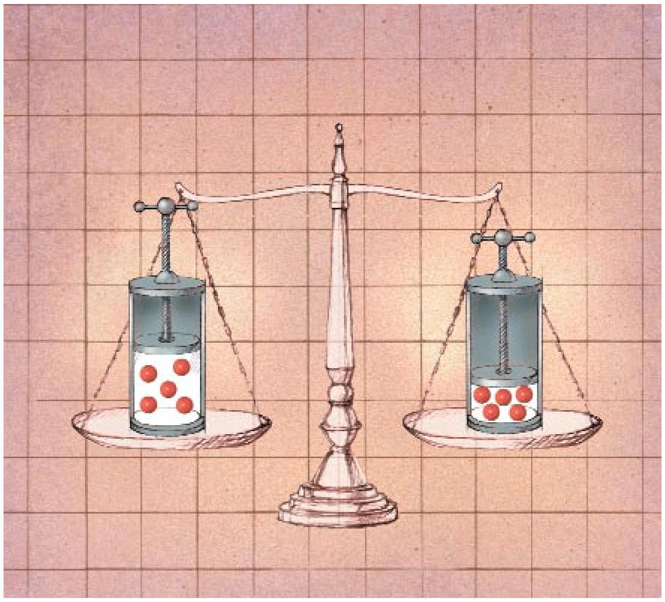
But there was something about those tiny particles—they kept popping up in inquisitive minds. One belonged to Thomas Harriot, an Englishman who went to the New World with Sir Walter Raleigh and wrote a popular book about what he saw there. Later, in a letter to fellow scientist Johann Kepler, Harriot suggested that Kepler "abstract and contract yourself into an atom" and enter "nature's house…. And when you…come out again, tell me what wonders you saw."

Robert Boyle (1627-1691), who was born in a castle a few years after Harriot died, was a prodigy (a young genius). In addition to being very smart, he was rich and lucky and had loving parents who took him on trips through Europe. When he was 14, he got to meet Galileo, the greatest scientist of that time—and one of the greatest scientists ever. (He'd already read all of Galileo's writings.) Galileo told him to study science. He took that advice.

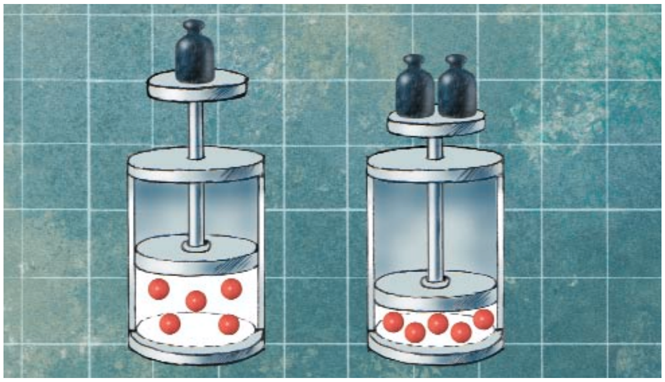
Boyle was fascinated with air; then no one knew it was made of several gases because no one had ever analyzed air—or any gas. In 1657, Boyle got his assistant, Robert Hooke, to design an air pump; with it, they were able to create a vacuum in a tube.

In 1663, Robert Boyle did a famous experiment with the pump, showing that if you take air in a large container and squeeze it into a smaller space, it will be smaller in volume but not in weight.

Later, he came up with what is known as Boyle's Law: *The volume of a gas is inversely proportional to the pressure put on it* (as long as its temperature stays the same). In other words, if you want to squeeze a volume of gas into half its space, you need to double the pressure put on it and vice versa. Boyle's Law, which really is quite simple, is a very important scientific milestone, although few took it seriously at the time. According to Samuel Pepys (PEEPS), who wrote about it in his diary, England's King Charles II "mightily laughed" when he heard the scientists at the Royal Society were "spending time only in weighing of air, and doing nothing else since they sat."



Boyle found that air could be squeezed into a smaller space without changing its weight.



From his experiments with air, Boyle figured out that the volume of a gas depends on the amount of pressure on it—doubling the amount of pressure cuts volume in half. Boyle then realized that air must be made of tiny particles and empty space— future scientists understood that those particles were atoms.

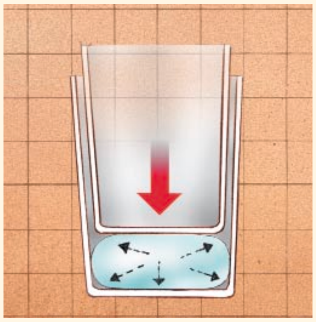
But some earnest scientists understood the importance of Boyle's Law. (It is still the starting point for much scientific research with gases, so it is worth rereading.)

Boyle's Law got scientific thinkers asking, "What can air be made of if you can change its size and shape without changing its weight?" Boyle said gases must be composed of tiny "corpuscles" (KOR puss ulz, little particles) and a lot of empty space, which is the reason a fixed amount of a gas can be squeezed from a big container to a small container. With his corpuscle idea, he was going back to the Greek theory of atoms. Isaac Newton, who was 15 years younger than Boyle (and, like Galileo, one of the greatest of all scientists), also believed in atoms. But he was so busy inventing calculus, finding the laws of motion, tracking down gravity, and studying light that he didn't have much time to work on the atomic idea. (It was Robert Boyle who financed Newton's great book on science, *The Principia*.) Though he didn't closely study atoms, Newton had a picture of those tiny par-

Test Boyle’s Ideas

Try to compress a liquid

Fill a balloon with a little water and tie the end. Try to squeeze it between two plastic beakers. You cannot squash the water into a smaller space.



Liquids cannot be squashed, so when you push on one part of a liquid, pressure is carried to all other parts of it.

Try to compress a gas

Blow a little air into a balloon and tie up the end. Try to squeeze it between two beakers. Unlike water, you can squash the air into a slightly smaller space.

Gases can be squashed, or compressed, into a smaller space. A compressed gas, like air in a balloon, pushes out equally in all directions. The more you compress a gas, the higher the pressure inside it.

Based on the 1997 edition of Annabel Craig and Cliff Rosney’s The Usborne Science Encyclopedia (*Usborne Publishing Ltd.*).

ticles in his head. He said, “It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles.” (Keep reading to see if he was right.)

Not many people paid attention to any of this. There didn’t seem to be a chance of actually seeing atoms. But, in Switzerland, a young mathematician named Daniel Bernoulli read Boyle and the Greeks and took those tiny corpuscles seriously.

What Creates Pressure in a Gas?

Daniel Bernoulli (burr NEW lee) wanted to be the Newton of the 18th century; he thought he could do it by studying fluids (by that he meant liquids and gases).

Daniel, who was born in 1700, had the background to go for it. His father, Johann, and his uncle, Jacob, were both world-famous mathematicians and they both hated Isaac Newton (who was now dominating the world of science). Daniel was another prodigy: he could deal with numbers at an amazingly early age. But his career wasn’t as easy for him as you might think; his father, Johann, was not your normal loving dad—he was jealous, nasty, and miserable.

Johann decided that his son would become a merchant and enter the family pharmacy business. But Daniel wanted to study mathematics. He was good at mathematics, and he was a terrible businessman. He failed as a pharmacist. Johann then insisted that his son Daniel go to medical school, but he did allow him to study mathematics on the side. Johann also answered his son’s questions, and, since Johann was one of the best mathematicians in the world, Daniel got very good training.

One of the things that preoccupied the great professor Johann Bernoulli was a little-studied phenomenon called *vis viva* (“living force”) in Latin. It was what we call energy, and no one understood it. Daniel was fascinated—*vis viva* was invisible, but clearly powerful.

When Daniel finished medical school—with top grades—he expected to get a professor’s job in Basel, and he wanted it to be in mathematics. He got no help from his father and ended up in Russia at the influential Academy of Science. His experiments and writings soon made him widely known. He began winning prestigious scientific prizes. He didn’t know it, but his father was fuming.

In 1735, both Daniel and his father wrote papers for the Paris Academy of Sciences, which gave a big prize that was much like today’s Nobel Prize. That year, the top prize was split; it was awarded to the two Bernoullis—father and son. Daniel came home to Basel. He thought his father would be pleased, but Johann was furious. He decided his son was trying to take over his position as Europe’s top mathematician. Johann threw his son out of the house, and Daniel never returned.

Now, all of that is like gossip, interesting but not really important. What Daniel accomplished though, became a landmark in science. As with so many achievements, it sounds simple, but no one else had figured it out.

Bernoulli considered motion and came up with a very useful principle. Strange as it may seem, when the speed of a fluid increases, its internal pressure decreases proportionately. Or: *As the pressure in a fluid goes down its speed goes up.*

If that simple theorem (idea) doesn’t interest you, don’t consider a career in engineering. You can’t design airplanes or ships or even bridges if you don’t understand Bernoulli’s principle. If you want to build a carburetor or an atomizer, where air is the moving fluid, you’ll use Bernoulli’s principle. In an aspirator, water (or another liquid) does what Bernoulli said it should do.

The principle, in simple language, is this: The faster a fluid (liquid or gas) is traveling over a surface, the lower its pressure. Engineers designing airplane wings know (thanks to Bernoulli) that the air flowing over the upper surface of an aircraft wing must move faster than air flowing beneath the wing. When that happens, the pressure will be lower on top of the wing, higher below the wing, and that will help the airplane lift.

That principle of Bernoulli’s also led to a “conservation” law that says the total energy in a fluid stays the same no matter what shape the fluid takes. If a liquid or gas goes from a big bottle into a smaller container, the speed of its atoms and the pressure of those atoms against the container will change but its total energy will not.

Daniel Bernoulli went even further than Robert Boyle in anticipating atoms. Bernoulli seems to have pictured them in his mind; he said it is the random, constant motion of atoms hitting the walls of a container that explains pressure in a gas. It was a remarkable deduction, since no one then could be sure atoms even existed.

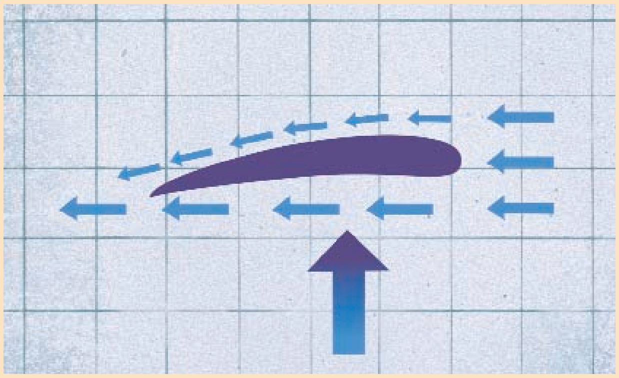
And no one had a clue that atoms are the key to elements, or that each element is made up of atoms that are almost the

See Bernoulli's Idea in Action

How do airplane wings work?

To see how wings work, blow hard over a strip of paper, and watch the paper rise.

The faster air flows, the lower its pressure. So as you blow, the pressure under the paper becomes greater than above it. This pushes the paper up.



The force pushing the wing up is called lift.

The shape of a wing is called an aerofoil. It is designed so air flows faster over the top of it. This lifts the plane up.

Based on the 1997 edition of Annabel Craig and Cliff Rosney's The Usborne Science Encyclopedia (*Usborne Publishing Ltd.*).

same, but different from atoms in other elements. Still, just believing in atoms and figuring out that they are in constant motion—well, that was an astonishing achievement. Getting the atomic idea down on paper as Boyle and Bernoulli did (even if they called them corpuscles), meant others could consider them.

Air Is Not an Element!

Scotsman Joseph Black (1728-1799) was a professor and physician. He was also an experimenter and full of curiosity. As a medical student, he got interested in kidney stones and then realized that minerals in the landscape and minerals in the body are similar. He began experimenting with them. He took some chalk (calcium carbonate, chemically known as $CaCO_3$), heated it with an alkali (a water-soluble base), and found that it gave off a gas. He called the gas "fixed air" because he found he could turn it back into calcium carbonate. We know the gas as "carbon dioxide."

Black's experiment showed that gases can be formed from ordinary solids. Gases, which had always seemed mysterious, were now seen to be chemicals that can be analyzed. Joseph Black, and others, began analyzing. (This was the Enlightenment, and scientific thinkers were helping to make the world understandable.)

Black found that carbon dioxide doesn't act like ordinary air. You can't burn substances in it, and you can't breathe much of it either. He figured out that some calcium carbonate (chalk or limestone in nature) weathers away naturally, becoming part of the air. Black realized that air, which since the time of Empedocles was believed to be basic and elemental, is actually a mixture of gases. That was a totally new idea. Empedocles was wrong—air is not an element!

Gases began to be taken seriously as states of matter, like solids and liquids. In 1766, Englishman Henry Cavendish (1731-1810) found that some metals, acted on by an acid, release a gas that is very flammable. He called it "fire air." We call it hydrogen and it is an element—colorless and odorless, the lightest of all the elements. In 1777, a Swedish apothecary, Carl Scheele, discovered another gas: oxygen. Like Black, Scheele realized that air can't be an element. He found that air contains oxygen and another gas, nitrogen. (He would later learn that it also contains carbon dioxide and still other gases.) Not knowing of Scheele's discovery (the publication of Scheele's results was delayed by his publisher), another scientist, Joseph Priestley, went on to discover oxygen a second time.

Priestley, a big-hearted, nonconformist English clergyman, was a friend of Ben Franklin. (While all this was going on, the British and the Americans were snarling at each other in Boston and Virginia and sometimes fighting.) Priestley, persecuted for his liberal religious ideas in England, headed for America.

Water Is Not an Element!

It was the late 1700s, and on the American continent, a bunch of radicals—George Washington, Thomas Jefferson, and John Adams are some of their names—were getting fed up with British rule. They were imbued with scientific curiosity, as most thinking people were during the Enlightenment (a time rooted in Newton's idea that nature has laws that bring order to the universe).

Politics would take much of the energy of the American revolutionaries. Still, they followed the progress of a young French tax collector who was trying to devote as much time as he could to scientific experimentation. The Frenchman had a head for figures, and also for details. He designed his own superb scientific equipment and spent much of his personal wealth building it. He recorded everything he did. He studied the work of the best of the alchemists (alchemists combined mysticism with experimentation).

The alchemists didn't weigh things with precision. The Frenchman did. He was a real scientist, so he didn't accept ideas he couldn't test and prove. The exact numbers that careful weighing gives make it possible to be mathematical and scientific.

Still, just believing in atoms and figuring out that they are in constant motion—well, that was an astonishing achievement.

Does water turn into earth as everyone believed? He decided to test for himself. He weighed some distilled water. Then he poured the water into one of two flasks connected by a tube so that the water vapor could go from one to the other. He sealed the flasks and heated them. The sealed system never changed weight. But, after 110 days, bits of residue had appeared in the water. He then weighed the dry flasks, the water, and the residue separately. The flask had lost weight equal to the weight of that residue. The alchemists said that water is "transmuted" (changed) into earth. With his accurate measurements, the Frenchman showed that the residue came from the flask, not the water. Water does *not* turn into earth!

The Frenchman said the new experiments with gases—the work of Boyle, Black, Priestley, and others—were like links in a giant chain that needed to be welded together. He decided he was the person to hold the torch.

When he learned that British experimenters had separated water into hydrogen and oxygen, he did his own experiments and confirmed their work. Now there was no question of it. Water is not an element! He later concluded that fire is not an element either.

The Frenchman realized that certain substances can't be further divided; he said they are the "elements." He understood and explained that idea to others.

The Frenchman's name was Antoine Laurent Lavoisier (ahn TWAHN lor RENT la VWA zee yay) and he has been called the father of chemistry.

III. Atoms and Molecules

Dalton Weighs Atoms

Experiments were proving that Empedocles' four substances—earth, air, fire, and water—were not the uncuttable elements he thought. But what about atoms? Robert Boyle (the Irishman who came up with the famous gas law) said that gases must be made of tiny "corpuscles" with a lot of empty space between them. Newton talked about "impenetrable" particles. Could Boyle's corpuscles and Newton's solid, massy particles be atoms? Lavoisier didn't think so. He didn't believe in atoms. Hardly anyone did, except Daniel Bernoulli (and Bernoulli's work would be ignored for almost 100 years).

Finally, an English Quaker named John Dalton came along and his timing was right.

Dalton was born in 1766 when winds of change had blown fresh air onto the European scene, and science, the arts, and political and religious philosophy were all hives of activity.

Otherwise, he didn't start off with good fortune. His father was a poor weaver who worked on a hand-loom and hardly earned enough to feed his family. Dalton was an awkward, colorblind boy with a weak voice. He was self-conscious and shy, but he was so bright that, at age 12, he was teaching in a small Quaker school. How would you like a 12-year-old teacher? His students didn't think much of the idea; they all dropped out.

Dalton went to a nearby village where he studied and even taught school again. At the same time he was doing experiments. He kept a journal that contained, along with other things, more than 200,000 meteorological notes. (Meteorology has to do with the weather.) His journal was published and that got him a job as a professor at New College in Manchester, England. New College was founded for Presbyterians and Quakers who weren't wanted at Oxford and Cambridge—universities open only to Church of England members. (Read some English history to understand why.)

But he didn't stay a professor long; he wanted to devote his time to research, which he did by living modestly and by tutoring students. He began work in chemistry, starting where Lavoisier (the Frenchman) had stopped.

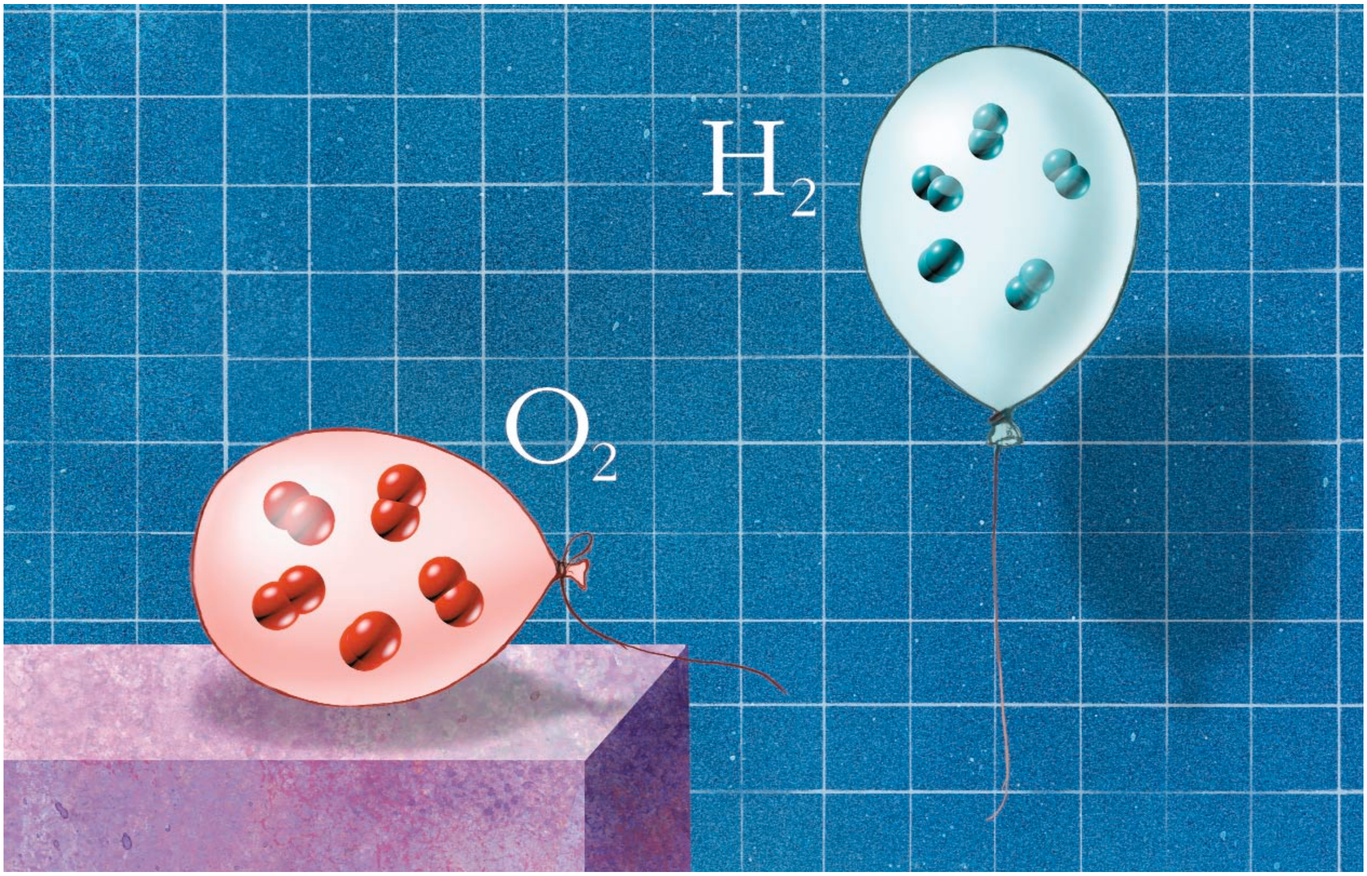
He understood that there are basic substances, known in science as elements—like iron, oxygen, hydrogen, sulfur, and carbon—that cannot be broken down into simpler components by chemical means. But what is it that makes one element different from the other? No one knew.

Dalton thought it might have something to do with atoms. Like Lavoisier, he did his own experimenting and measured with scientific precision. But he went still further. "An enquiry into the relative weights of the ultimate particles of bodies is a subject, as far as I know, entirely new," he wrote, describing the path he had chosen.

But there was no way (then or now) to weigh or measure an individual atom. What could he do? Because of the study of gasses—like hydrogen, oxygen, and nitrogen—Dalton knew that elements always combine in fixed amounts with the same ratio of weight one to another. There is nothing random about it. (It's called "the law of definite proportions.") That give him a breakthrough thought.

Imagine a crate with an equal number of red cups and green saucers. It falls off a forklift: CRASH. You now have a heap of green shards and another of red. You need to know the relative weight of a cup and a saucer but you don't have either. What do you do? You weigh each pile and compare their weights. That ratio between the pile of red and the pile of green is the ratio of the weight of one cup to one saucer.

Dalton knew that if he weighed equal amounts of elements, he could assume equal numbers of atoms and get the ratio of their weights. He still wouldn't know the exact weight of an atom, but he would know how it compared to others. He correctly guessed that hydrogen was the lightest element. He used that as a standard; all the other elements became multiples of that lightest one. It wasn't difficult, but he was the one who got the idea to try it. Once he figured out some relative atomic weights, he could draw conclusions.



After thinking about other scientists' work and doing some experiments of his own, Avogadro was convinced that equal volumes of any two gases contained the same number of molecules (as long as they were at the same temperature and pressure). So, even though H_2 *molecules are lighter than* O_2 *molecules (since hydrogen atoms have less mass than oxygen atoms), a balloon full of* H_2 *gas would have the same number of molecules as a balloon full of* O_2 *gas. This insight was another big step in deducing that atoms exist.*

Dalton said each element has unique atoms; it is the weight of its atom that identifies an element. (He was basically right, but today we know that atoms are complex. There's a reason for those differing weights. More on this below.)

Dalton's insights led him to ideas that are the basis for modern atomic theory. He said that *every atom in an element is alike and has the same weight;* and *atoms of different elements have different weights.* He prepared a table of atomic weights. He was way off on some of them, but it was a start. (Be sure you understand the difference between mass and weight. We now think in terms of mass, not weight.)

Dalton went on to say that *atoms can neither be created nor destroyed* and that chemical reactions are just rearrangements of atoms.

He understood that atoms that are unlike can bond in a "firm union" to form substances that are not elements—they are *chemical compounds.*

Dalton realized that there is a difference between mixtures (where atoms can exist in almost any proportions—as in air) and compounds (where atoms exist in set proportions and no other—as in water). But he didn't know about molecules, which are groups of two or more atoms bonded together. And he didn't know about some maverick atoms, called isotopes, which are slightly different from their sisters. Most important, he had no idea that atoms have innards and that the number of protons inside each atom determines its characteristics. Dalton talked of "atomic weight"; today, we talk of atomic number, meaning the number of protons. Still, he took a huge step by taking atoms seriously.

When he published his theories in 1808, people paid attention—he became a celebrity. (As I said, his timing was right.) Even the king asked to see Dalton. To be presented to the king meant wearing breeches, buckled shoes, and a sword. Quakers don't wear swords, and Dalton didn't have fancy clothes. What was the shy, awkward scientist to do? He solved the problem by dressing in a university robe. When he died, 40,000 people filed past his coffin. Many didn't understand atoms, but they did understand that this man had helped explain their world.

Atoms turned out not to be solid and impenetrable as Democritus and Newton thought. They were not like hard billiard balls as Dalton described them. In the 20th century, a nucleus and still smaller particles (called neutrons, protons, and electrons) would be found inside atoms. As the 21st century began, the search for yet smaller particles—perhaps pulsating strings really thought to be uncuttable—was under way. But atoms—Dalton's atoms—are still the smallest form of an element having all the characteristics of that element. Knowing that gave science a huge insight into the way the world works.

Molecules

Amedeo Avogadro (ah me DAY oh ah voh GAH dro) took the next step in understanding atoms. He was born in 1776 (an easy date to remember). Avogadro was a count from Italy's Piedmont (northern foothills). His full name was Lorenzo Romano Amedeo Carlo Avogadro conte di Quaregna e di Cerreto and he started out as a lawyer, but was so fascinated with scientific research that he gave up law to be a professor of physics.

Avogadro figured out that most matter—gases, liquids, and solids—is made up of particles containing two or more atoms held in a tight embrace. He named those particles "molecules" (from the Latin word for "small masses"). We believe he was first to distinguish between atoms and molecules.

Water (a compound) is composed of molecules made of unlike atoms—so is carbon dioxide. Hydrogen (an element) is usually found in molecules with two like atoms bonded together (H_2).

Understanding the difference between single atoms and combinations of atoms (molecules) may sound simple, but it was a big step. That idea of atoms and molecules is the foundation of modern chemistry.

Dalton told us that *the smallest form of an element (with all the characteristics of that element) is an atom.* Avogadro told us that *the smallest form of a compound is a molecule.*

Then, Avogadro came up with a law of his own—known naturally as Avogadro's Law. Here it is: *Equal volumes of all gases (at the same temperature and pressure) contain equal numbers of molecules.* Think about that—it gives scientists a very useful measure to work with.

Avogadro used that law to get the correct formula for water. No one had done that before. When a quantity of water is broken apart into hydrogen and oxygen and those gases are collected separately, the hydrogen takes up two times the space of the oxygen. According to Avogadro's Law, if the hydrogen occupies twice the volume, there would have to be twice as many hydrogen molecules. That's how Avogadro figured out that the formula for water is H_2O, not HO as Dalton believed.

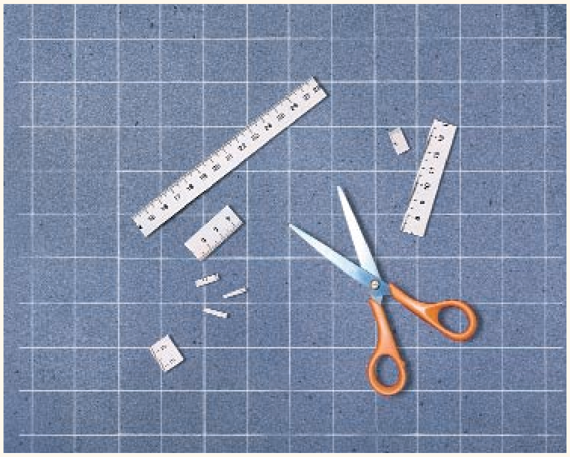
Avogadro's insight would eventually lead to a way to calculate the number of atoms in a given quantity of any element. (Today, it is called Avogadro's number.)

At about the same time Avogadro was doing his work with molecules, a poor boy named Michael Faraday was working in a book bindery. There he bound and read a new section on electricity in the *Encyclopœdia Britannica* (to be published in 1810). It helped him find his life's work. Eventually, Faraday's discoveries in electricity would lead to electric generators, electric motors, and much, much more.

But his first fame came as a chemist. Faraday figured out laws of electrolysis; electrolysis is the use of an electric current to break apart compounds, like H_2O. If something couldn't be broken apart, he realized it must be an element. Faraday's laws seemed to confirm that matter is made up of small particles. No one could see those particles, but Faraday assumed they were there—and when he did, his laws worked.

Meanwhile, Avogadro's molecules were ignored. Avogadro was one of those people whose ideas are mostly rejected while they are alive. But if you don't understand molecules you can't do much with atoms. So atomic research didn't get

Just What Size Is an Atom?



Investigate the world of the very small by cutting a 28 centimeter strip of paper in half as many times as you can. If you can cut the strip of paper in half 31 times, you will end up with a piece of paper the size of an atom.

What you'll need

1 strip of paper 28 centimeters (11 inches) long
1 pair of scissors

What to do

Take your strip of paper and cut it into equal halves.
Cut one of the remaining pieces of paper into equal halves.
Continue to cut the strip into equal halves as many times as you can. (And be sure to keep count!)
Make all cuts parallel to the first one. When the width gets longer than the length, you may cut off the excess, but that does not count as a cut.

So, how far did you get?

Here are some comparisons to think about!

Cut 1	14.0 cm	Child's hand, pockets
Cut 2	7.0 cm	Fingers, ears, toes
Cut 3	3.5 cm	Watch, mushroom, eye
Cut 4	1.75 cm	Keyboard keys, rings, insects
Cut 6	0.44 cm	Poppy seeds
Cut 8	1 mm	Thread – Congratulations if you're still in!
Cut 10	0.25 mm	Still cutting? Most have quit by now.
Cut 12	0.06 mm	Microscopic range, human hair
Cut 14	0.015 mm	Width of paper, microchip components
Cut 18	1 micron	Water purification openings, bacteria
Cut 19	0.5 micron	Visible light waves
Cut 24	0.15 micron	Electron microscope range, membranes
Cut 31	0.0001 micron	The size of an atom!

From The Atom's Family Web site: **www.miamisci.org/af/s/n/phantom/papercutting.html.**

anywhere and, as time passed, atoms began to be called "useful fiction." That's not hard to understand—atoms are beyond belief small.

Just what size is an atom?

Imagine magnifying one drop of water until it is 15 miles wide; you would then begin to see the atoms inside the water molecules (not clearly—that would take much greater magnification). Do you understand why no magnifying microscope can see atoms? (Today, scanning tunneling microscopes "see" them electronically.)

Or, picture an apple. Blow that apple up until it is the size of the Earth. Each of its atoms is now the size of a normal apple.

Here's another image: 250 million hydrogen atoms packed side-by-side will stretch about an inch in length.

As for molecules, chemist Brian L. Silver writes, "Molecules tend to be very small entities... if the whole population of Earth set out to count the molecules in a teaspoon of water, each person counting at the rate of one molecule per second, it would take over a million years."

Scientist Lewis Wolpert says, "There are many more molecules in a glass of water than there are glasses of water in the sea." We know things like that because we have Avogadro's number to help with the calculating.

Imagine figuring out that atoms and molecules exist. What Dalton and Avogadro and Faraday did was astonishing. But you may not be surprised to hear, as time passed, many scientists began to reconsider Dalton's theory. They even made fun of it, just as they had ridiculed Democritus's atoms. No one would ever be able to see an atom, the skeptics said. They were absolutely sure of that. Would you have believed in atoms and molecules?

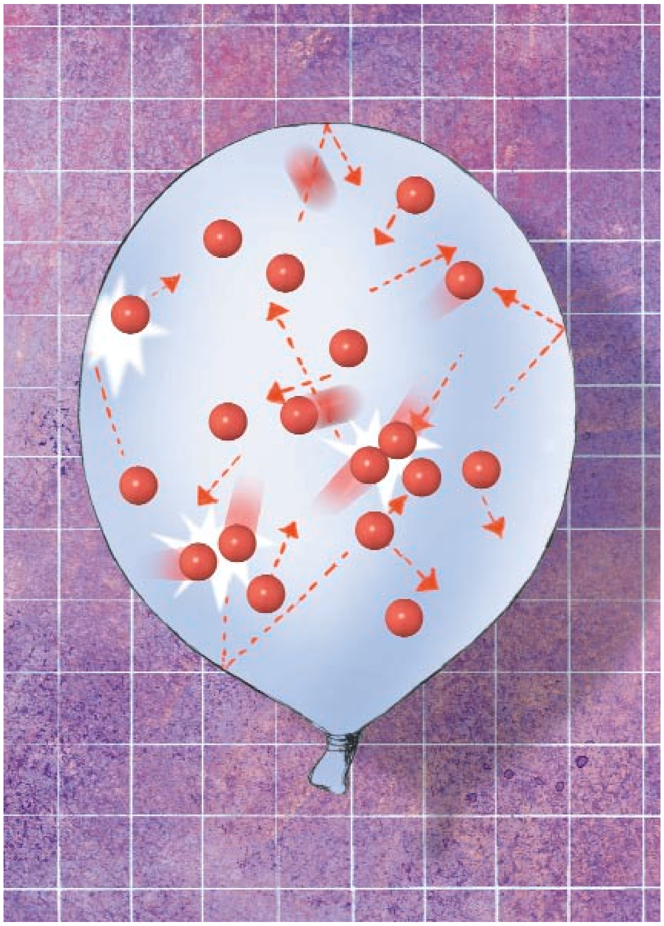
Bulldog Boltzmann

Ludwig Eduard Boltzmann had a big nose, big ears, a bushy red beard, and a head thick with curly brown hair. Only his glasses were small. They had wire rims, and he peered through them with nearsighted eyes. A student sketched him on a bicycle—a portly professor with coattails in the air. There's charm in the sketch as there must have been in the man.

Boltzmann was a physicist and, in the late 19th century, one of the stars of his profession. He could be intimidating—he was intense and very learned—but he was also kindhearted. He couldn't bear to give his students low grades, and he usually didn't. They adored him. One of them, Lise Meitner (who became a famous atomic scientist herself) wrote, "He was in a way a 'pure soul,' full of goodness of heart, idealism, and reverence for the wonder of the natural order of things." For him, physics was a battle for ultimate truth.

Boltzmann was born in Vienna, Austria, in 1844. His childhood couldn't have been easy: By the time he was 15, his father, brother, and sister had all died. He was schooled at home by tutors. One was the composer Anton Bruckner who got fired by Boltzmann's mother after he threw his wet raincoat on a bed. Nonetheless, Boltzmann became an accomplished pianist.

But it was as a scientist that he made his mark. When he was still a student, a professor handed him some papers by the Scottish scientist James Clerk Maxwell. He also gave him "an English grammar…since at that time I did not understand one word of English." Boltzmann didn't need to translate the mathematical equations—they are a universal language—but he struggled with the English until he understood that, too. Maxwell impressed him above all other scientists of his day. "As with a magic stroke everything that earlier seemed intractable falls into place," he wrote.



Boltzmann was sure that gases were made of tiny particles that move around bumping into each other and the walls of their containers. (He was right—that's the pressure that keeps a balloon inflated.)

Some scientists believed atoms and molecules were just metaphors—convenient fiction that helped explain things mathematically—but Boltzmann was convinced that Maxwell's equations described a real world of atoms and molecules. He studied gases and their behavior. He knew that the amount a gas can be compressed can be explained if the gas is composed of a vast number of tiny entities (atoms and molecules) that bounce around and collide with each other and the walls of their container. (It's that kind of pressure that keeps a balloon inflated.) Bernoulli and Avogadro had understood the movement of atoms and molecules, and Boltzmann paid attention to the ideas of both of them. By the time Boltzmann came along, Avogadro's ideas were finally getting some attention.

Boltzmann couldn't see those atoms, but he could measure their behavior. His approach was based on statistics and measurement, and they led to his "kinetic theory" of gases, Ernst Mach thought atoms were a convenient fiction. "Have you ever seen one?" he would taunt when Boltzmann lectured.

which became an important part of the science of thermodynamics. (THERM-oh-die-NAM-icks—thermo is a prefix meaning heat; dynamics means motion, so does kinetics.)

Boltzmann was fascinated by thermodynamics. The steam engine, which was changing his 19th-century world, had gotten scientists thinking seriously about heat. They knew steam has power—it can move an engine. But they couldn't agree on what heat is. It was a big question that needed solving. Is heat a property of matter, or is it matter itself?

When it came to heat, Boltzmann built on an experiment done by an American, Benjamin Thompson, who was often called a traitor. Thompson, a Loyalist during the American Revolution, fled the United States for England, came back and led British forces, was knighted by the king, and then moved to Munich, where he became Count Rumford. Science remembers him for his experiment with horses and a boring tool demonstrating that heat isn't a substance, but is created by motion. But Rumford didn't take the next step and tie heat to atoms, Ludwig Boltzmann did. He figured out that it is the motion of atoms and molecules that creates heat. He even came up with a formula to measure the speed of molecules in a gas. He had it right, but hardly anyone noticed.

Most scientists of his time, especially many in Germany, just would not believe in atoms. Have you ever had an idea that seems perfectly clear and true and yet no one else seems to get it? Talk about frustration! That's what Boltzmann faced. History is full of cycles and, by the late 19th century the spirit of open inquiry that marked Enlightenment times had receded. It was a hard time to get new ideas accepted.

So Boltzmann became a battler. He kept fighting for that atomic idea. Ernst Mach (pronounced MOCK), another well-known Austrian physicist, was one of those who thought atoms were a convenient fiction. "Have you ever seen one?" he would taunt when Boltzmann lectured. England's Lord Kelvin (William Thomson) also rejected the idea of atoms and molecules, and Kelvin was an important scientist with international clout. (So was Mach.)

Don't worry, change was on the way. Can you feel the tremors in the scientific world? Those tremors—like vibrations before an earthquake erupts—were only noticeable to a few people with keen senses. They could tell that something big was about to happen. It had to do with the atom—proofs were coming. The unbelievers would soon have to admit atoms exist. But even those who believed in atoms weren't prepared for all that was ahead.

At the end of the 19th century, fewer than half of all scientists believed in atoms. And those who did thought atoms were like billiard balls (those solid balls found on a pool table). Isaac Newton said atoms are hard and impenetrable, and so had just about everyone since then—including John Dalton and Ludwig Boltzmann.

But, they would learn, atoms are much more interesting than billiard balls, and much more complex. They are little worlds in themselves, but no one knows that in 1900, as the century turns.

IV. Atoms Come of Age

A Boy with Something on His Mind

Fifteen-year-old Albert Einstein was miserable. He was trying to finish high school in Germany, but he hated the school (a strict, rigid place). To make things worse, his parents had moved to Italy where Albert's father owned a factory that built parts for machines—called *dynamos*—that take energy from coal, oil, or mountain streams and convert it into electricity. His parents thought he should stay behind until his schooling was completed. It wasn't long, though, before he was on his way over the Alps heading south to join them. Why did he leave Germany? Today, no one is quite sure, but a letter from the school offers a powerful clue, "Your presence in the class is disruptive and affects the other students," it reads.

What were the Einsteins to do with their son? How would your parents react if you were a high-school dropout?

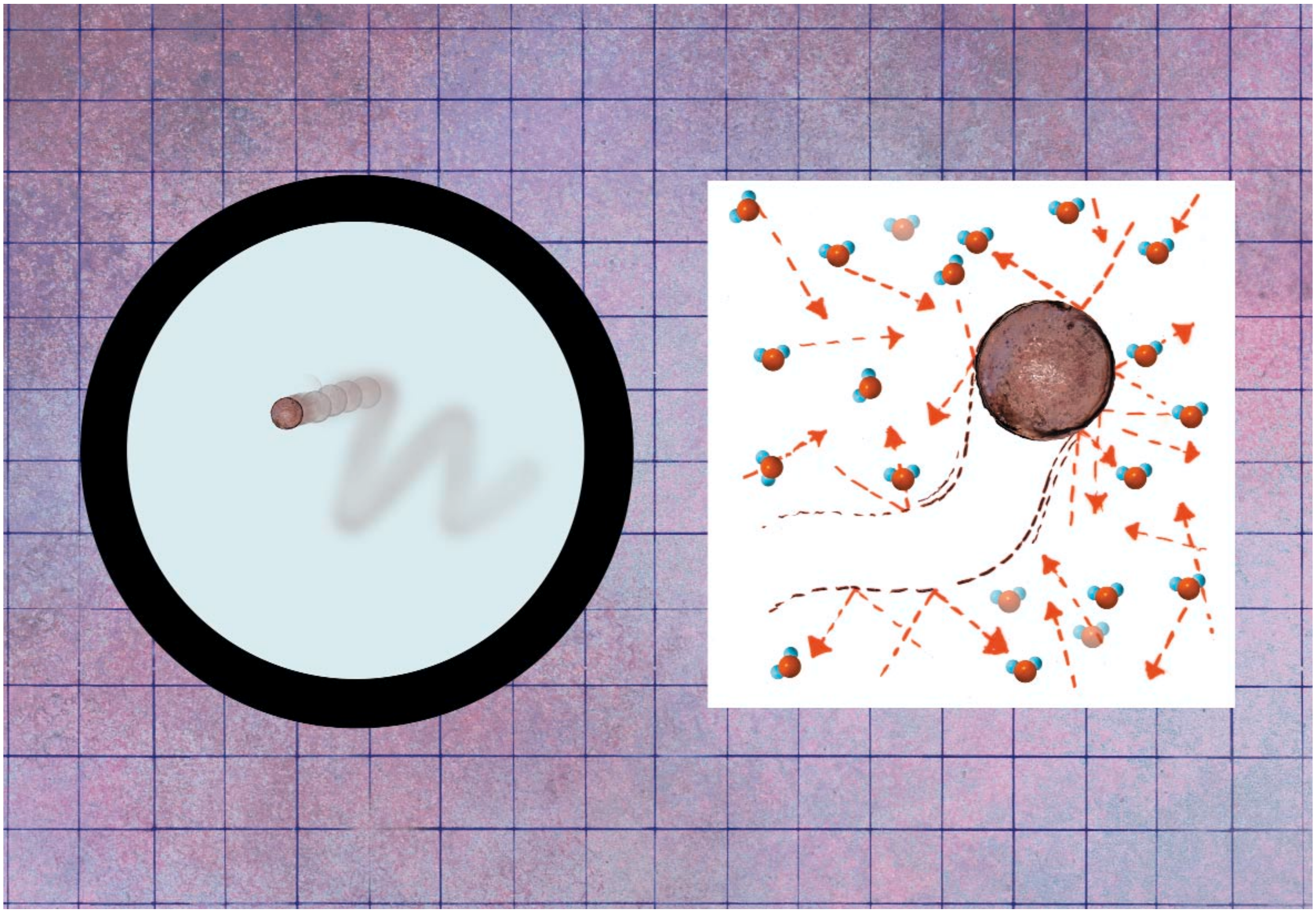
While everyone in the family was worrying about his future, young Einstein's mind was somewhere else. There were questions that wouldn't leave his head: "What would the world look like if I could sit on a beam of light?" he kept asking himself. Are there really atoms—bits of matter too small to be seen by any ordinary microscope? In 1894 (when he was 15), no one had the answers to his questions.

What made Albert Einstein focus on those puzzles? No one knows for sure, but 15 is a good age for questioning. And Einstein, at that age, was already well-grounded in mathematics and the new sciences. He was lucky; he had been born into the right family.

His parents were interested in books and ideas and conversation. Einstein said his father was "very wise." (But he wasn't much of a businessman; his factories kept failing.)

Einstein's Uncle Jacob introduced him to mathematics. His mother read him the best books she could find and introduced him to music. His violin became a friend; he learned to play it well. And then there was a regular dinner guest. His name was Max Talmey, and he was studying to be a doctor. It was a tradition for Jewish families to invite poor students to dinner. Max came every Thursday, bringing the latest ideas in science and mathematics to the dinner table. When Albert was 12 years old, Max gave him a geometry text that Einstein later called his "holy geometry book." Max shared many other books and later wrote that his eager young friend had soon gone far beyond him in mathematical knowledge.

When Albert was 13, Max lent him a book by the German philosopher Immanuel Kant. It was very tough reading,



Brownian motion was a mystery to Brown, but Einstein understood that it was the motion of the water molecules that caused the pollen to dance about. In the drawing above, the left side shows what Brown saw through his microscope—a piece of pollen that inexplicably moved in water. The right side shows what Einstein saw in his mind—water molecules moving about and bumping into the pollen. (In reality, the pollen is millions of times larger than the water molecules.)

but Einstein was always willing to struggle with anything that he thought worth the challenge. Kant tried to connect all the great ideas of philosophy into one embracing system. Later Einstein would try to do the same thing in science.

But his deep reading hadn't helped at the stern German school (called a "gymnasium"), where no one dreamed that what the questioning young Einstein was doing would lead to a new model of the universe.

After he arrived in Italy, his parents suggested he come down to earth. The family factory wasn't doing well. Albert had to find a career. He said he wanted to be a high school teacher, so he was sent off to school in Switzerland to finish high school and prepare for a university. There he boarded with a friendly family, and the Swiss school—in a town named Aarau—turned out to be just right for him. It had outstanding teachers, high standards, and an informal atmosphere. Students were expected to ask questions and search for answers. Fifty years later he still remembered it as a place where everyone joined in "responsible and happy work."

From Aarau, Einstein went to Zurich, Switzerland, to the Federal Institute of Technology (one of Europe's leading technical universities), where he studied physics and mathematics. Zurich, in the heart of Europe, was a lively city with cafés and conversation that attracted artists, writers, and political thinkers from many lands. (Russia's Lenin and Ireland's James Joyce were two of them.) There was only one woman in his class, a Serbian, Mileva Maric. She was a pioneer, one of the first women to study advanced physics anywhere in the world. Einstein must have been impressed.

Meanwhile, he managed to annoy most of his professors. It was clear that Albert Einstein was bright, but he had an attitude problem. He had little patience with schoolwork and often didn't appear in class; he seemed to learn best on his own. When he graduated and needed a job recommendation, he couldn't get one. One of his teachers called him a "lazy dog" because he didn't always do his assignments. But the professor was wrong. Einstein wasn't lazy. His mind was working hard. "In all my life I never labored so hard," he wrote to a friend about one occasion of deep thinking.

He finished his studies at the Swiss Federal Institute of Technology (in 1900). But he didn't have a doctorate and his university record was not very good—he had angered some of his teachers, they didn't recommend him—and he couldn't get a teaching job. He was desperate; he wanted to marry Mileva.

He sent letters off to some scientists he admired looking for work, but none answered. So Einstein put an ad in the Berne newspaper offering to teach physics to private students for three Swiss francs an hour. Still, that wasn't enough to live on, and he often went hungry. Finally, in June 1902, he was hired as a technical expert, third class, at the patent office in Berne. Seven months later, he and Mileva Maric married and, before long, had two sons. (The marriage would fail.)

The patent office turned out to be a good place for him. He had a boss who was strict but fair. "More severe than my father—he taught me to express myself correctly," said Einstein. Day after day, he examined applications for patents on inventions. Each application came with a model. He had to decide, and quickly, if the invention was worthwhile. Should it be given a patent? Then he had to describe the invention and give the reason for his decision—all in a few words. That was good mental training, especially as his boss would only accept precise, careful reports.

The job left him time to think for himself, which was what he was really meant to do. He thought and thought and thought about discoveries that were ricocheting in the world of science. One scientist claimed to have discovered tiny particles called electrons, that were even smaller than atoms. Others seem to have found radioactive energy rays coming from inside atoms. This was at a time when most scientists still didn't believe atoms even existed!

A distinguished German scientist named Max Planck had solved a puzzle about something called radiant energy. He showed that it could be explained mathematically if the energy were assumed to be in "chunks" (or particles or bullets) rather than only in a continuous wave. Planck called those tiny chunks "quanta." Einstein couldn't stop thinking about light; now he had those quanta to consider, too. Could light be made of quanta? Two years later, in1905, the obscure patent clerk published five scientific papers. Four were in a physics journal, *Annalen der Physik*—three in the same issue. (Copies of that issue are now rare and very valuable.)

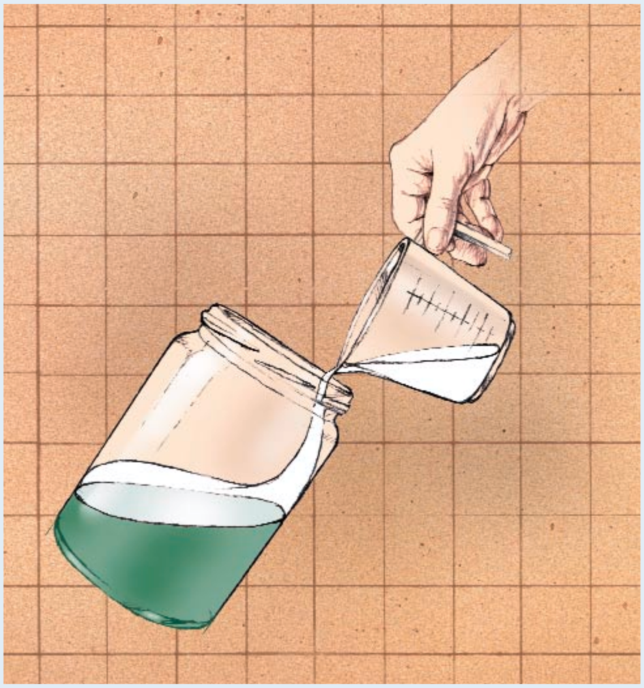
Suppose you'd been a physics professor in 1905, would you have paid attention to articles written by a young patent clerk who didn't even have a doctorate? It was amazing: A few people *did* pay attention. Some knew this was the work of a scientific genius. One of the first to take notice was a distinguished professor—Max Planck.

Test Einstein's Idea of Brownian Motion

Are water molecules really moving around all of the time?

See for yourself. In a 1-quart jar, mix together one teaspoon of sodium chloride (table salt), five drops of green food coloring, and one cup of water. Tilt the jar and slowly pour a second cup of water down the inside of the jar. The result is a layer of green water covered by a layer of clear water.

Place the jar where it can remain undisturbed for three days. Observe the contents of the jar as often as possible. (But don't touch it—you don't want to shake up that water.) The two layers of water will start to mix. The reason? The water molecules are moving just as Einstein reasoned. The end result is a uniformly green-colored liquid.



Based on Janice Van Cleave's A+ Projects in Chemistry: Winning Experiments for Science Fairs and Extra Credit (*John Wiley & Sons, Inc.*).

Thirty-eight years later, a group of scientists floated particles in a liquid, sealed them under glass, and then watched for a whole year. The particles kept moving.
No one could fathom why.

Classical science has a miracle year (in Latin called an *annus mirabilis,* AH nuss mere AH bih liss). It is 1666, the year of Newton's greatest productivity. Modern science also has an *annus mirabilis.* It is 1905, the year of those four articles in the *Annalen der Physik.*

Two of Einstein's articles were about special relativity (which deals with the speed of light and travel at high speeds). One was about Max Planck's quanta and one was about something called Brownian motion, which had to do with atoms.

Brownian Motion...and Atoms

Fifty-two years before Einstein was born—about the same time that John Quincy Adams was president of the United States and the peerless composer Ludwig van Beethoven was on his deathbed in Germany—a Scottish botanist (a plant scientist) named Robert Brown looked through a microscope at tiny bits of pollen floating in water and noticed something puzzling. The pollen was dancing about, even though the water seemed still. What made it move? Could the pollen be alive? Brown didn't think so, but he wasn't sure. Being a careful scientist, he decided to float some other microscopic particles in water. He used old dried pollen, powdered tar, ground-up arsenic dust, and other things he knew had no life. The particles all moved actively. The moves were like a jitterbug or breakdancing, with jumps here and there. Brown called it a "tarantella," which is a Spanish dance. What caused the movement? No one knew.

Scientists spent years debating about that random movement—which came to be called "Brownian Motion." Thirty-eight years later (the year the American Civil War ended), a group of scientists floated particles in a liquid, sealed them under glass, and then watched for a whole year. The particles kept moving. No one could fathom why.

They didn't realize that they could have kept watching and watching, and the dance would have gone on and on. If they had been able to preserve the sample in the glass jar, we could see the same Brownian motion they saw (and so could our grandchildren). It is ceaseless. Why? What makes it happen?

Einstein, in one of his 1905 papers, argued that Brownian motion is caused by the action of atoms in the molecules of water. Those billions of water molecules move very rapidly, he said, bumping and banging the pollen.

No one could see the water molecules, they were much too small for the microscopes of the time. Einstein figured this out in his head, but not all by himself. As you know, the idea went back to Democritus—who lived in Greece long before the birth of Christ. Democritus had conceived of atoms as the basic building blocks of nature and then said that they are in constant motion, even in a substance that seems at rest. Einstein knew of the ancient atomic theories and he knew of John Dalton and Ludwig Boltzmann and those 19th-century scientists who believed in atoms. He also knew that some scientists of his day didn't take them seriously.

How can you believe in something you can't actually nail down? Many scientists still thought molecules and atoms were fictional devices that were helpful in working out formulas, but that it was unscientific to believe in something that you can't actually see. The physicist Ernst Mach was the skeptic who kept asking, "Have you ever seen one?" Einstein admired Mach.

But Einstein ignored his question. Instead, he thought about the problem of Brownian motion and came up with a solution. It was mathematical. He figured out statistically how the water molecules would behave if they were there.

Einstein devised a formula that said that the distance the particles move increases by the square root of the time considered. In other words, in four seconds the particles will move twice as far as they do in one second, not four times as far.

He was convincing and he was right: Billions of unseen but active water molecules were moving the visible particles of pollen. That statistic-based theory could be tested experimentally.

"By 1908, the French experimental physicist J. B. Perrin had tested and confirmed Einstein's formula," said Jeremy Bernstein, a physicist, professor, and author of several books on popular science. "Moreover, by actually observing the distance that the Brownian particles traveled, [Perrin] was able to deduce approximately the number of molecules per cubic centimeter in the liquid through which they were traveling."

Read that again to be sure you understand its importance. Einstein's reasoning didn't just answer the questions of Brownian motion, it helped prove that atoms and molecules exist. It proved that statistics can be taken seriously in the creation of scientific theories. His explanation and the follow-up tests managed to convince the skeptical scientists—those who had been unwilling to believe that atoms are real. It was a sweet victory for the atom.

The End

(Actually, this is not an end at all. It is the beginning of the Atomic Age, to be followed by the Nuclear Age—and that may be the point of this article: Science, like knowledge, keeps going, and growing, and that is why it is so much fun.)