25 The Right Man for the Job

At this moment there emerged one of those men who can stand above the whole scene, look at the confused pieces of the jig-saw puzzle and see a way of turning them into a pattern.... In 1772, when he was twenty-eight, he surveyed the whole history of the modern study of gases and said that what had hitherto been done was like the separate pieces of a great chain which required a monumental body of directed experiments to bring them into unity.

—Herbert Butterfield (1900–1979), British historian, *The Origins of Modern Science*

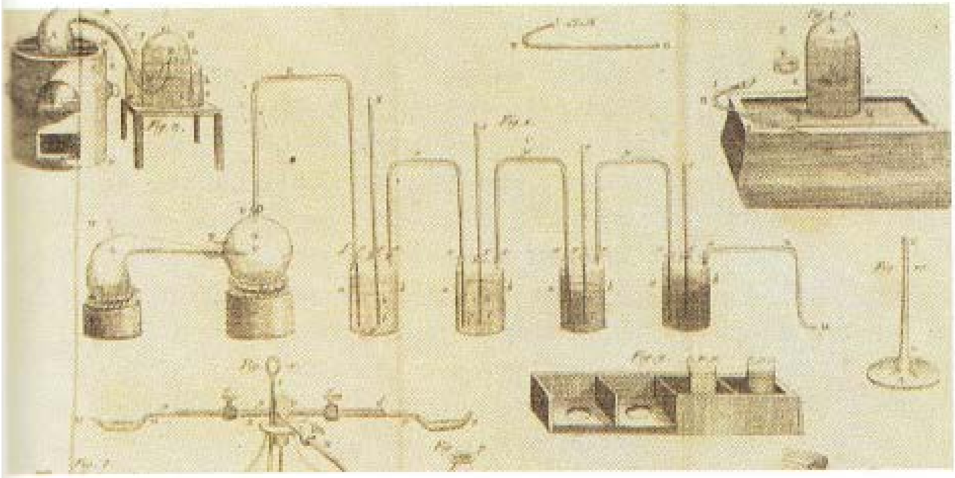
He really did two things. He drew the distinction between elements and compounds, so that people understood the way that the world was built much more clearly; and he found a way of attaching numbers to chemistry....As soon as you attach numbers to anything, you turn science into physical science and that gives you an enormous predictive power to investigate your ideas very precisely.

—P.W. Atkins (1940–), British chemist, as quoted in *On Giants' Shoulders* by Melvyn Bragg

It is the late 1700s, and on the American continent, a bunch of radicals—George Washington, Thomas Jefferson, and John Adams are some of their names—are getting fed up with British rule. They are imbued with scientific curiosity, as most thinking people are during the Enlightenment, but politics is taking much of their energy.

Still, they have time to follow the progress of a young French tax collector who is trying to devote as much time as he can to scientific experimentation. The Frenchman has a head for figures, and also for details. He designs his own superb scientific equipment and spends much of his personal wealth building it. He keeps a careful record of

CHEMISTRY is sometimes defined as the study of the laws that govern the behavior of the elements. Here's a definition by English chemist John Read: "Chemistry is the branch of science which deals with the study of matter, or in other words with the character of the 'stuff' of which the material universe is composed." Today chemistry and physics often merge.



To distill water (or any liquid), you boil it, capture the vapor, and let it cool back into liquid form. Why? Because a lot of impurities—salt, minerals, dirt, and so on—are left behind. In this illustration of the process from *Elements of Chemistry*, note the pelican instrument in the upper left corner.

everything he does. This man is a real scientist, and although he studies the work of the best of the alchemists, he doesn't accept ideas he can't test and prove.

The alchemists combine ingredients to make their concoctions, but they rarely weigh things with precision. The Frenchman does. (He builds balance scales to do it.) Careful measurement is essential in science.

In this book, you will find me describing measurements as "precise" and "exact." Be aware: I don't really mean it. Today's scientists will tell you that—despite our most sophisticated equipment—there is no such thing as an exact measurement.

Does water turn into earth, as is widely believed? The Frenchman decides to test for himself. He weighs some distilled water and also weighs a glass vessel called a pelican because of its curvy, long-beaked shape: (see image at right, and above, top left). Then he pours the water into one flask of the pelican, seals the container, and boils the water so that it all condenses into a second flask. The sealed system never changes weight. But after 101 days, bits of residue have appeared in the flasks. He then weighs the flasks, the water, and the residue separately. The pelican has lost weight equal to the weight of the residue. The alchemists say that water is "transmuted" (changed) into earth. With his precise measurements, the Frenchman has shown that the boiling water broke away bits of the flasks, and the residue comes from the glass, not the water. Water does *not* turn into earth!

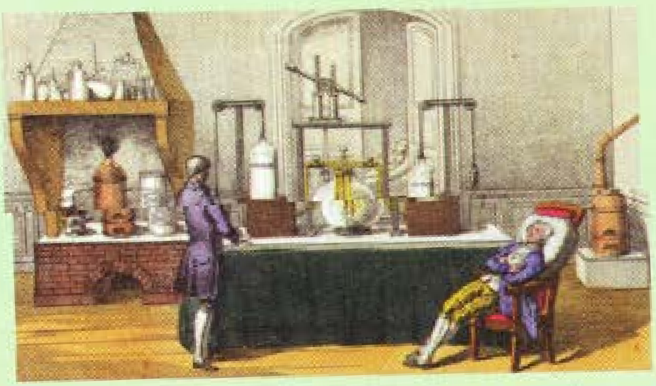
O NOTES

Oxygen, vital for life, is in almost every molecule in our bodies. It is the most abundant element in the Earth's crust, where it often combines with other elements to form oxides in rocks and minerals.

As a gas, oxygen makes up about 20.95 percent of Earth's atmosphere, where it is the diatomic molecule O_2. (*Diatomic* means each molecule is made up of two atoms of the same element.)

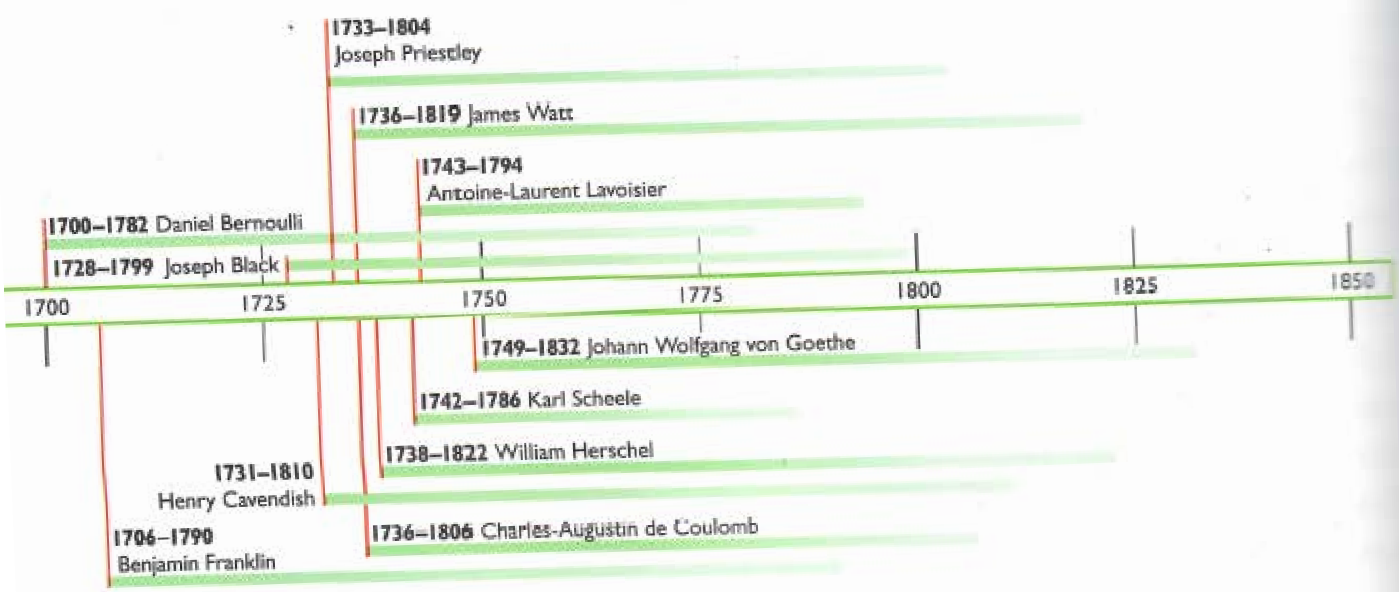
What's ozone?

It's O_3, a triatomic, or triple-atom molecule, that wasn't discovered until 1840. Ordinary oxygen is odorless and colorless, but ozone ranges from colorless to dark blue-violet, depending on density. It has a strong, sweet odor that you can sometimes smell after a thunderstorm: lightning creates ozone. Ozone can be a byproduct of automobile exhaust and is harmful to plants and lung tissue. Ozone in the stratosphere—the Earth's upper atmosphere—shields Earth from the Sun's harmful ultraviolet radiation.



At left is an engraving of scientist Antoine Lavoisier doing two things: combining hydrogen and oxygen into water and studying the respiration of a sleeping man. Several experimenters had exploded "inflammable air" and found that it condensed into water. Lavoisier named that air *hydrogène*, from the Greek for "water creator."

When he learns that British experimenters have separated water into hydrogen and oxygen, he does his own experiment and confirms their work. Now there is no question of it: Water can't be an element; it is composed of two gases.



The Frenchman is sure that there *are* certain substances that can't be further divided: they are the elements. When elements combine, they create compounds (like water) which can't be easily broken apart.

He understands that air is neither an element nor a compound. He figures that out when he discovers that rusting objects do not lose weight, as everyone thinks; they gain weight. His measurements confirm this. But how can that be? He hypothesizes that the rusting object is attracting some kind of particle from the air. That turns out to be oxygen. If air can release the gas oxygen and still seem to be air, then air must be a mixture of gases and not a compound.

Some things never change. Mass is one of them. It may change shape, but not value. Its value remains constant. It is invariant. The idea that there is no loss of mass through combustion *in a closed system*—is called **the Law of Conservation of Mass.** It's an important law. Put it in your head. We'll get to it again.

RUSTING AND BURNING—YOU CAN BLAME (AND THANK) OXYGEN

Rust is a slow form of oxidation (oxygen bonding with a substance). A bike that rusts gains weight because oxygen combines with its steel (high in iron) to make iron oxide (Fe_2O_3). This happens through a series of chemical reactions that require both air and moisture.

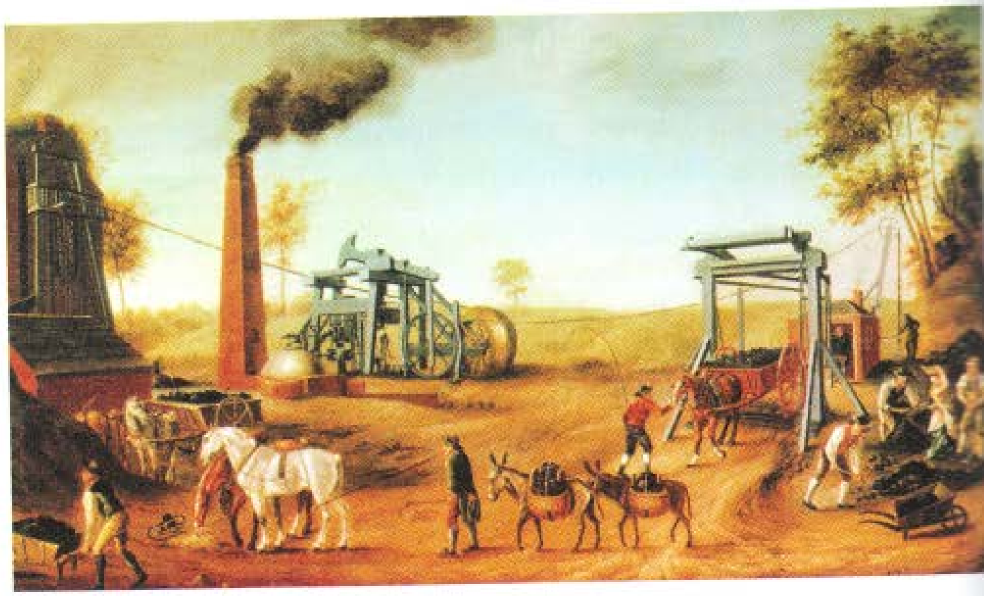
When an apple bruises or a slice of apple turns brown, oxidation is happening. Damaged cells in the apple are breaking open and spilling their guts—including molecules of acids. There's oxygen in the air and in the apple (that's why apples float). It combines with the acids (with the help of an enzyme) and turns them brown.

When foods turn rancid (rotten), it is often because of oxidation. The idea behind vacuum-packed foods is to get rid of the oxygen.

Burning is a quick method of oxidation—and a major source of energy. When a car engine combusts (burns fuel), the fuel is undergoing an explosive process of oxidation—one that releases a lot of heat energy. In a more low-key oxidation process, your body burns the nutrients in food as fuel for energy. Oxygen in your cells combines with carbon chemicals like glucose (a sugar), releasing heat energy and carbon dioxide.

While oxygen bonds easily, it's not the only reactive substance. Today the term *oxidation* has broadened so that oxygen doesn't even have to be involved. Anytime one substance strips away the electrons of another, it's called oxidation. (More about electrons and other smaller-than-atom particles to come).

To the naked eye, a nail looks shiny. But during oxidation, seen under a high-power microscope (left), the surface is covered with a corrosive oxide layer known as rust.



Joseph Black's assistant, James Watt, used the new knowledge about gases (especially Boyle's Law) to design an improved steam engine. Steam engines turn the plentiful energy found in wood and coal into mechanical work. Those engines were first used to pump water out of coal mines. (Miners were dying in flooded mines.) Soon the engines were moving coal itself out of mines. But Watt's engine could do much more than just move coal: it could turn looms, power locomotives, and drive ships. When that was understood, the Industrial Revolution really steamed ahead. At right is a contemporary painting of one of Watt's steam engines.

He isn't the one who discovers oxygen—others beat him to that—but he is first to announce that oxygen is an element.

The Frenchman not only studies the experiments of Boyle, Black, Priestley, and Scheele—he does them all again, so he can be sure of the results. He says those experiments are like links in a giant chain that need to be welded together. He decides he is the person to hold the torch.

The Frenchman thought oxygen was essential for combustion. Later it was found that some other gases can also be used in the process.

When he burns a log of wood, he is left with ash and smoke. Most of the mass of the log seems to be gone. But when the Frenchman burns objects *in closed containers* and then weighs the residue—very carefully—the weight stays the same. He realizes that burning (combustion) doesn't change the amount of matter in the universe. It just changes its form. (This is a really important concept.)

Mass is never lost. It can change, but it can't be eliminated. Scientists call that a conservation law.

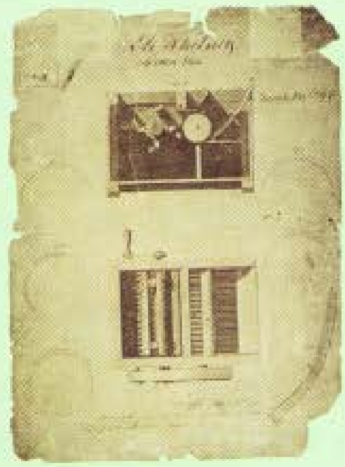
Mass is never lost? Thanks to Albert Einstein, we now know that mass and energy are interchangeable, according to his famous formula: $E = mc^2$ (E is energy; m is mass, and c is the speed of light). Right now, the Sun is changing tons of mass into the energy we call sunshine. But no one understood that in the nineteenth century.

And that still isn't all that this man uncovers. He finds that **combustion is a chemical reaction between two or more substances** (usually oxygen and something else) **that gives off heat and light.**

What about phlogiston? A belief in that theoretical substance is taught in schools. But his description of combustion leaves no need for phlogiston. He realizes: **There is no fire element; there is no phlogiston.** Discovering that is like taking chains off a captive: it sets

REVOLTING TIMES

Was revolutionary fever contagious? When the Americans rebelled against British rule in the 1770s, they were after political freedom. They would get what they wanted. Economic freedom was another issue. By 1790, the Industrial Revolution was accelerating in Great Britain. New textile machines had been invented there, and at about the same time, some technological geniuses, such as James Watt, figured out ways to use steam to power that machinery. This was a big deal. It would change the way goods are made and at the same time lower prices and spread prosperity. But without the secrets of the new technology, other nations, like the infant United States, had to buy goods from England.



Eli Whitney was a Yankee who went south, saw the need for a way to separate cotton fibers from seeds, and invented a machine (above). Unexpectedly, it made slavery profitable. At right is his patent drawing.

The British wanted to keep a monopoly on their new productivity; they tried to erect a wall of secrecy around their island. That's never easy. Merchants in the United States offered a big reward to anyone who could build spinning and weaving machines in the U.S. When cotton-spinner's apprentice Sam Slater arrived with plans for a spinning machine memorized in his head, the Industrial Revolution had made it across the ocean. Then in 1793, Eli Whitney invented the cotton gin (*gin* is short for "engine"), which furthered the revolution and changed the economy of the American South and the future of slavery.

Meanwhile in France, another freedom revolution was brewing. In October 1789, a Parisian crowd, angered by rising bread prices, marched to the royal Palace of Versailles, captured the king and queen, and demanded a new constitution. At first it looked as if France would have a constitutional monarchy, but then the revolution got out of hand, as you'll see in the next chapter.

science free from the burden of a wrong idea.

Who is this Frenchman? His name is Lavoisier (lah-vwah-zee-AY), Antoine-Laurent Lavoisier (1743–1794), and he is often called the Father of Chemistry. He is handsome, and his wife, who is part of the story, is beautiful. He intends to do for chemistry what Isaac Newton has done for physics—write a book that will bring together all the knowledge in the field. He will do what he intends and more. He will create a revolution in science.

When Lavoisier read his paper on phlogiston (saying that there is no such thing) to the Royal Academy, he was interrupted by jeers. The members had a hard time accepting a new idea.

26 A Man with a Powerful Head

We ought, in every instance, to submit our reasoning to the test of experiment, and never to search for truth but by the natural road of experiment and observation.

—Antoine-Laurent Lavoisier (1743–1794), French chemist, *Elements of Chemistry*

Hypotheses are the scaffolds which are erected in front of a building and removed when the building is completed. They are indispensable to the worker; but he must not mistake the scaffolding for the building.

—Johann Wolfgang von Goethe (1749–1832), German poet and scientist, *Maxims and Reflections*

The substances that fill our universe can be burned, squeezed, shredded, or hammered to bits, but they won't disappear. The different sorts floating around just combine or recombine. The total amount of mass, however, remains the same.... With all of Lavoisier's accurate weighing and chemical analysis, researchers were able to start tracing how that conservation happened.

—David Bodanis, (1956–), American science historian, *$E=mc^2$*

His parents expect Antoine-Laurent Lavoisier to be a lawyer, like his father and his grandfather before him. So he goes to Paris to study law. But this is the enlightened eighteenth century, and in most universities everyone seems to be talking about the latest scientific discoveries. Lavoisier hears a science professor lecture, and he is captivated. He goes back again and again to hear more lectures.

It is soon clear that his real interest lies in science, not law.

But scientists have no way to earn a living—at

We have just seen that all the oxides and acids from the animal and vegetable kingdoms are formed from a small number of simple elements.... We may justly admire the simplicity of the means employed by nature to multiply qualities and forms.

—Antoine-Laurent Lavoisier, *Elements of Chemistry*

In this 1789 French engraving, a hardworking peasant is carrying a nobleman and a priest on his back. The title: *Il faut espérer que le jeu finira bientôt.* It means "Let's hope the game will be over soon." The game? That's the political system that seemed to exploit the working class. It took the French Revolution (1789–1799) to change that game.

least not the kind of prosperous living Lavoisier has always enjoyed. He is determined to be a scientist and to live well too. So he makes what seems to him a smart investment. He buys a share in the company that collects taxes for the king. That brings him a handsome income, and it also allows him time to concentrate on science.

The king's taxes are especially onerous (OH-ner-uhs—it means "burdensome") to the peasants. Tax systems almost always seem to favor the rich (who have influence) and penalize the poor (who don't).

Lavoisier supports efforts to reform the French tax-collection system, but he doesn't get far. When crops fail and some peasants starve, Lavoisier loans them money without interest. He helps set up an old-age-pension system for farmers. He serves on education committees. He investigates hospitals for the poor and makes recommendations to improve them. But, no question about it, being a tax collector gives him wealth and privileges at the expense of others.

It gives him something else too—a wife.

The chairman of the French tax-collection firm has a daughter. She happens to be a beautiful and talented artist. When they marry, Marie-Anne Pierrette Paulze is 13 and Antoine-Laurent Lavoisier is more than twice her age. (Thirteen-year-old brides are not uncommon in these days.) The age difference doesn't matter: she has a mind that keeps pace with his.

The Lavoisier home becomes one of the liveliest and most elegant in Paris. Almost every night, guests are invited for

Each day Lavoisier sacrificed some hours to the new affairs for which he was responsible. But science always claimed a large part of the day. He arose at six o'clock of the morning, and worked at science until eight and again in the evening from seven until ten. One whole day a week was devoted to experiments. It was, Lavoisier used to say, his day of happiness.

—Mme. Lavoisier (1758–1836), writing about her husband

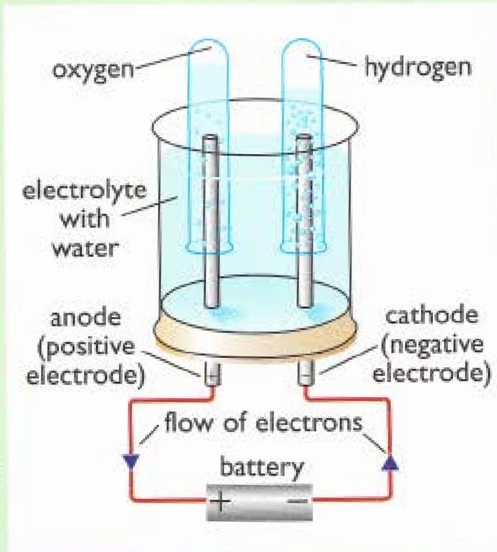
This is a portrait of Antoine-Laurent and Marie Lavoisier painted by their friend Jacques-Louis David. Notice the portfolio of drawings on the chair. Those are Marie's drawings. If you study the work of most artists of this period, you will see stiff people dressed in classical gowns. David changed all that. He did the same kind of thing in art as Lavoisier did in science: he made it real. A director of the Metropolitan Museum of Art in New York City has said that this painting is the greatest of all neoclassical paintings. You can see it in that museum and decide if you agree.

dinner and conversation. Ben Franklin comes often, as does Jacques-Louis David (France's leading painter and Marie's teacher and friend). James Watt discusses technology (he is Joseph Black's assistant and a designer of steam engines). Gouverneur Morris (who wrote much of the American Constitution) adds charm as well as intellect. Felice Fontana (an Italian scientist renowned for his research on snake venom) is a frequent visitor. Thomas Jefferson, a special friend, brings his violin and astonishes everyone with the range of his interests. The physician Joseph Guillotin adds social concerns to the conversation. Guillotin proposes that a mechanical decapitation (head-chopping) machine be used in capital punishment. His idea seems more humane and technologically advanced than hanging people or whacking off their heads with an axe. The dinner guests talk of the latest technology as well as of science, art, music, politics, and fine foods.

During the day, the Lavoisiers work. When the king wants to improve gunpowder production, he asks Antoine for help, and the job gets done. Lavoisier studies street lighting in Paris. He puts shades over his windows, and for six weeks works in darkness studying all the fuels he can find. He decides that Paris's streets can be most efficiently lit with olive oil. (He wins a prize for that work.)

When he "sparks" hydrogen and oxygen with an electrostatic charge and produces water, he awes an audience. (Who would have thought that two gases could turn into a liquid?) Working with a geologist on land maps, he understands, before almost

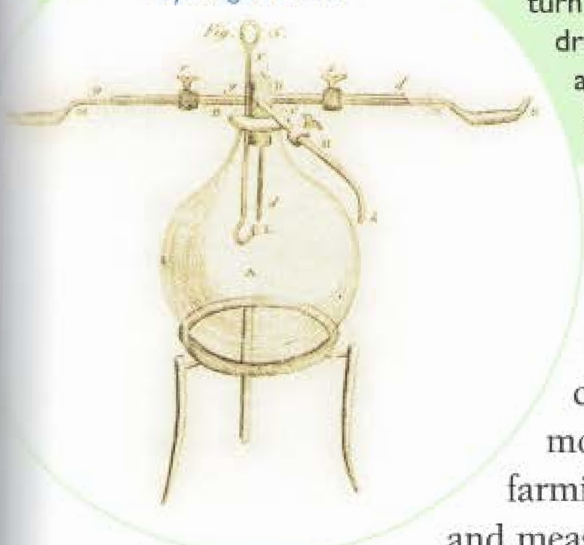
HOW ELECTROLYSIS WORKS



Henry Cavendish, Joseph Priestley, and Antoine-Laurent Lavoisier used an electrostatic device to "spark" oxygen and hydrogen and turn them into water. Only Lavoisier understood that water is a compound of the two gases; the others included phlogiston in their chemical equations. Today fuel cells turn hydrogen and oxygen into drinking water on spacecraft and power cars that run on hydrogen instead of gasoline.

Electrolysis is about sticking two rods called electrodes (the negative and positive poles of a battery) into a liquid—in this case, water. Electrons flow from the battery to the negative rod (the cathode), through the water, and back to the battery by way of the positive rod (the anode) in a circuit. At the anode, water molecules give up electrons (they become oxidized), producing oxygen. At the cathode, water molecules grab electrons and are reduced to hydrogen gas. (Reduction is the opposite of oxidation.) Water has two hydrogen atoms per oxygen atom, so electrolysis produces twice as much hydrogen gas (right tube).

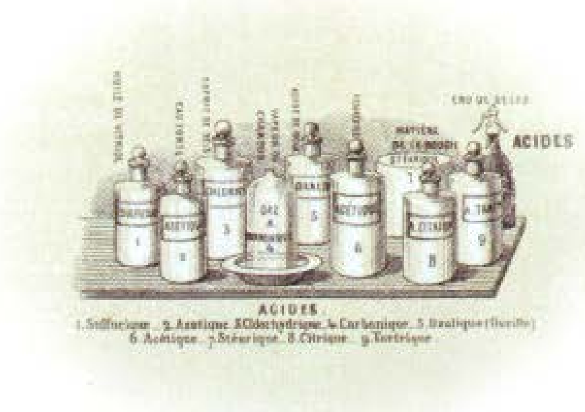
Lavoisier's hydrogen burner

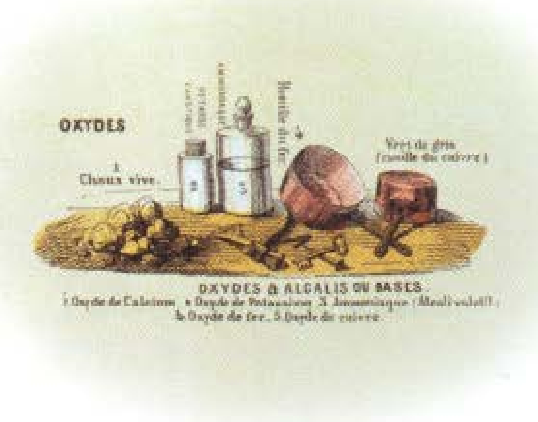


anyone else does, that Earth's layers tell a story of geological time and change. He designs a model farm using scientific farming methods: he weighs and measures the seeds he sows, the fertilizer he uses, and the crops that are yielded—at a time when most people are just guessing about those things. George Washington writes from Virginia, asking for news of Lavoisier's farming methods.

With his methodical mind, Lavoisier reorganizes the tax system and makes it more efficient. But when he decides to build a wall around Paris to make sure that no one gets in or out without paying a tax, he makes enemies. Not surprisingly, most Parisians hate that wall.

Joseph Guillotin (1738–1814) was a French physician and inventor of the guillotine, an execution machine designed to chop off heads quickly and cleanly.





Above are examples of acids (left) and oxides (right) from a nineteenth-century French engraving. An oxide is a combination of oxygen and another element—calcium, potassium, iron, and copper in the detail on the right. Oxides of metals are normally bases (or alkalies) and react with an acid to produce a salt.

PURE SCIENCE is science for science's sake—researching to add to our knowledge of the world. APPLIED SCIENCE is using that knowledge toward a practical end—lighting streets efficiently, growing more crops, making better gunpowder, and so on. Lavoisier did both, but today, scientists tend to choose one or the other.

At age 25, he is accepted as a member of the prestigious French Academy of Sciences; the next youngest member is 50. That academy immediately puts him on committees to study gravity, bleaches, water supplies, prison conditions, and so on. He knows that clear writing will give his ideas power, so he writes his reports in elegant, lucid prose. Eventually he becomes head of the academy—which means serving on more committees and doing still more work. It doesn't seem to slow down his research into pure science.

He starts out where Boyle left off and demolishes the Greek concept of earth, air, fire and water—once and for all. Then he comes up with a clear definition of **an element: It's any substance that can't be broken down into simpler substances.** Next, he creates a useful classification system. He searches out, lists, and organizes all the known elements, grouping them in a table by their properties. He finds 33 elements. He isn't right about all of them. Some are compounds—like silica and magnesia—but this is groundbreaking work and not easy. His basic idea is right even if some of the details are wrong. He says light is an element (wrong) and also something he names "caloric" (wrong again).

Caloric? Lavoisier realizes that combustion (burning) is a chemical reaction that uses oxygen and gives off heat. But what is heat? He doesn't know. When he puts a hot coal next to a piece of ice, the coal's heat melts the ice. What's going on? Lavoisier says that an invisible fluid must move from the burning coal to the lump of ice. It's that invisible fluid (which he has theorized) that he calls "caloric."

He's really off-course when he calls caloric an element and includes it in his table. By now he has a great reputation, so most scientists go along with this theory. Actually the caloric idea does help scientists analyze heat's properties. When they think they are measuring "caloric," they are actually measuring heat. Hypotheses, even if wrong, are often an important step in the scientific process. They give you a place to start. Then you can prove or disprove them and go on from there.

If you don't come up with a hypothesis, or reasoned guess, you can't go anywhere and, mostly, Lavoisier is heading in the right direction. One of his most important ideas is that concept of **conservation of mass** (now expressed, thanks to Einstein, as conservation of mass-energy). He understands that while things may change shape or form, nothing is lost or gained in nature. (Think about that idea—it's a big one.)

Lavoisier serves on a commission that helps get the metric system started. He thinks up a naming system for chemicals. He brings order to a disorderly field. When he writes the book he had planned—bringing together everything known in chemistry—he and his wife celebrate by burning the books of the alchemists. (Book burners are usually nasty sorts, but the Lavoisiers are trying to make the point that alchemy belongs on the trash heap.)

Lavoisier's book, *Traité Élémentaire de Chimie* (1789), or *Elements of Chemistry*, is sometimes compared to Newton's *Principia* (as Lavoisier intended). It lays the foundation for modern chemistry.

How does Lavoisier manage everything? He schedules his days

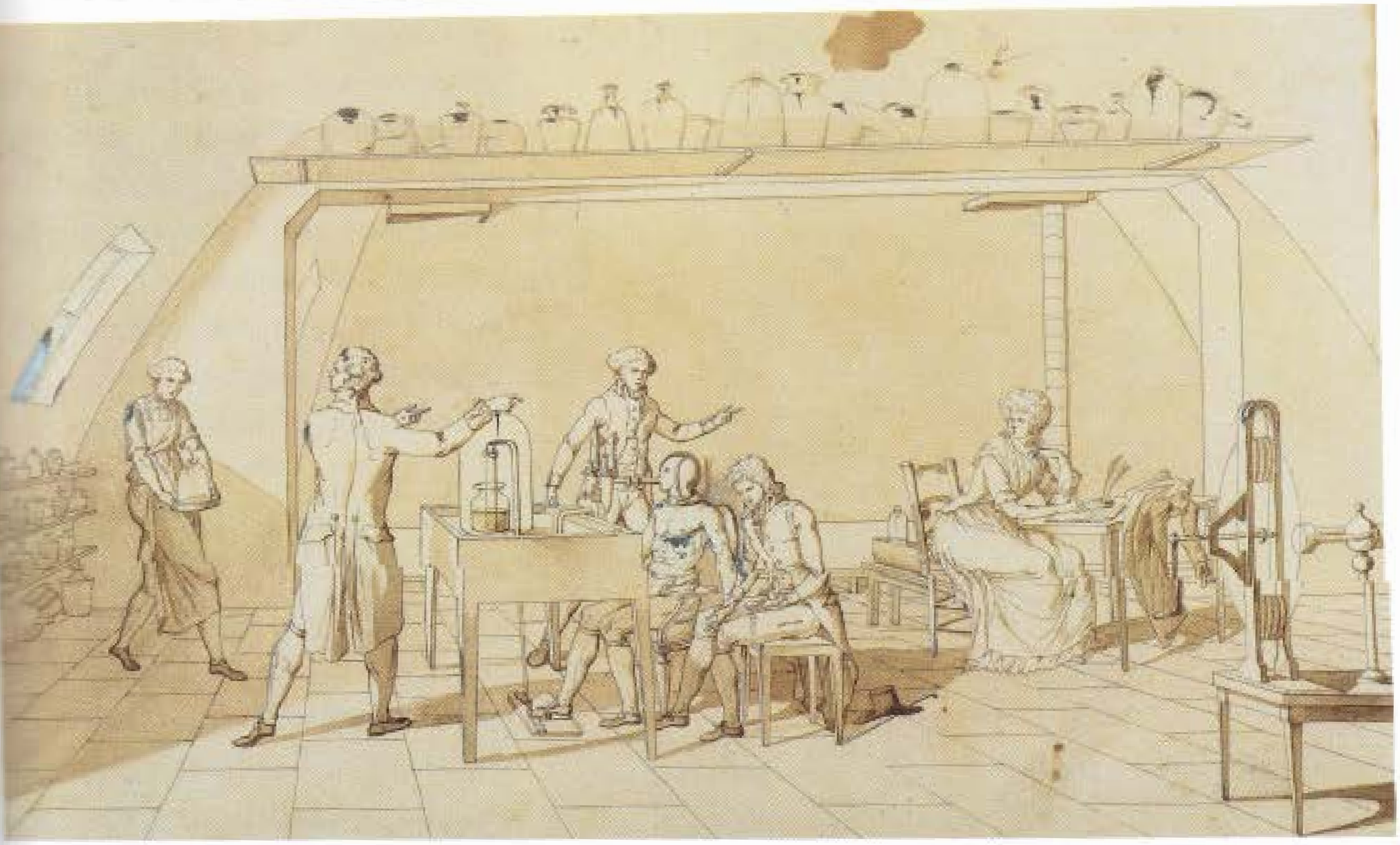
Iron oxide was known in England as "astringent Mars saffron," and zinc oxide was "philosophic wool." But in France they had other names. When Joseph Priestley came to dinner at the Lavoisiers' house, he spoke of "red lead." No one knew what he meant. (He was talking of lead oxide.)

Clearly something had to be done. Chemistry needed a common language. Lavoisier and Guyton de Morveau established a system of chemical nomenclature. For instance, they gave a compound of a metal and a nonmetal the suffix *-ide* (like iron oxide). Their system is still used today.

TERRIFIC TEXTBOOK! (AN OXYMORON?)

Lavoisier's *Elements of Chemistry* laid the foundation for modern chemistry. Newton's *Principia* laid foundations in physics. Unlike Newton, Lavoisier wrote clearly. People could understand what he said. That gave his book special influence. Here's part of his preface:

> *Every branch of physical science must consist of three things; the series of facts which are the objects of the science, the ideas which represent these facts, and the words by which these ideas are expressed. Like three impressions of the same seal, the word ought to produce the idea, and the idea to be a picture of the fact. And, as ideas are preserved and communicated by means of words, it necessarily follows that we cannot improve the language of any science without at the same time improving the science itself.*

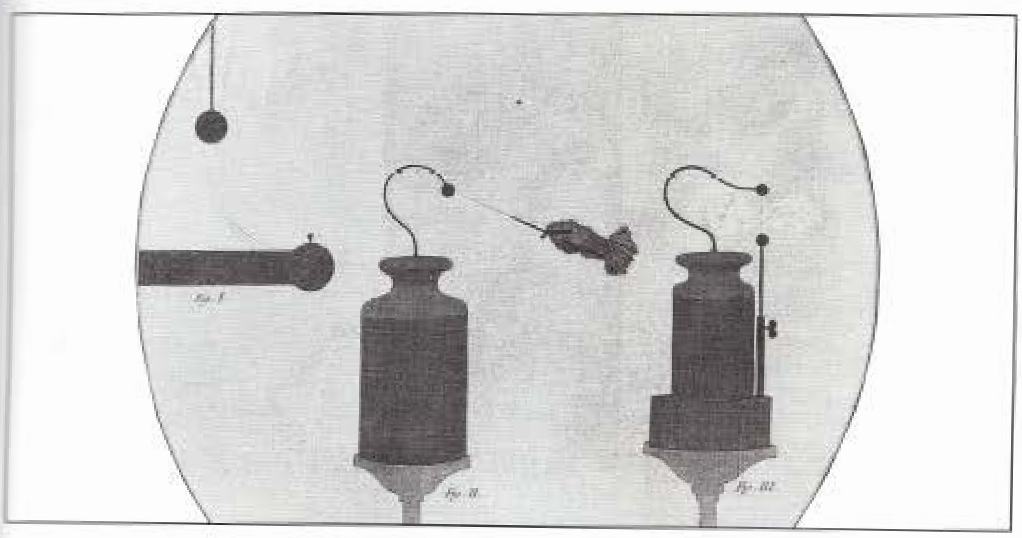


carefully—and he works in tandem with his wife.

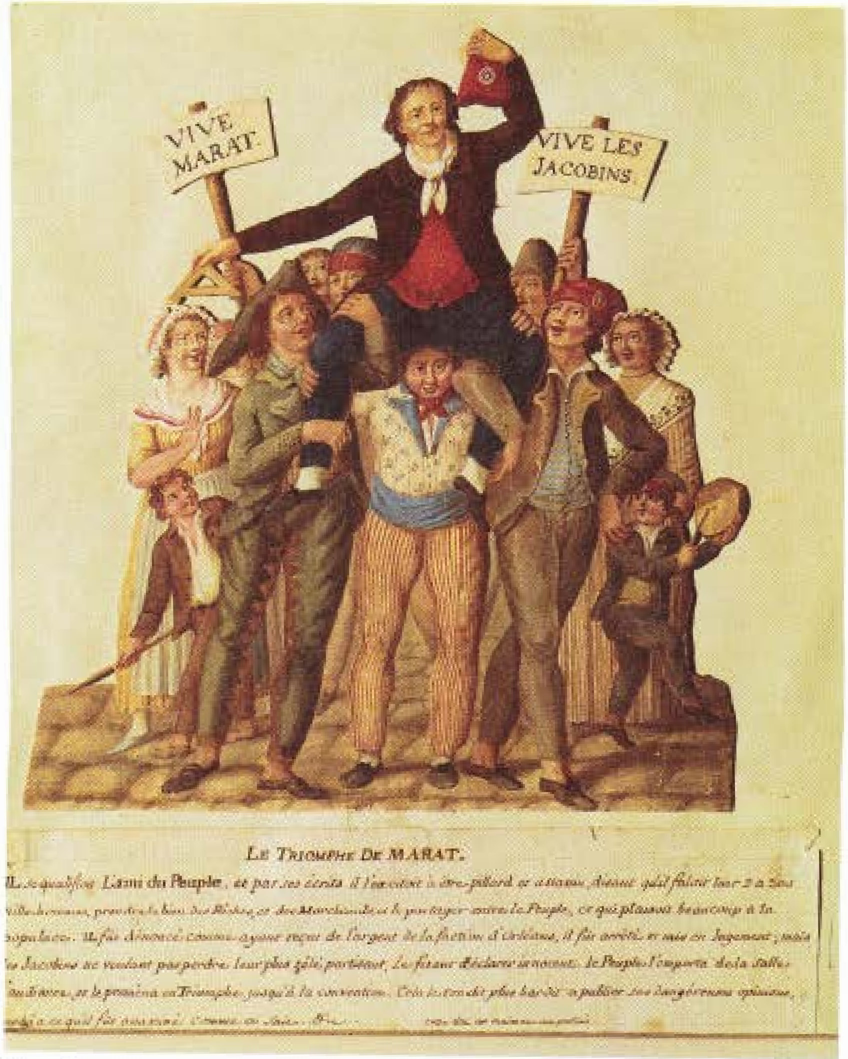
Antoine does precise experiments and records each of them carefully. Marie makes detailed drawings that are another clear record of their work. The alchemists have been haphazard about science; the Lavoisiers set ground rules for those who follow. They turn chemistry into an exact science.

Because she has a talent for languages—and Antoine doesn't—Marie learns English and then Latin. She reads and translates the work of scientists from other lands.

Marie Lavoisier drew this sketch of her husband and his assistants. (That's her, sketching away, on the right, above.) Lavoisier and his assistants are collecting a man's breath to analyze the gas content for a study on respiration.



This illustration is from a book on electricity by Jean-Paul Marat (1743–1793), who believed he was snubbed by the scientific community. Shown here are Leyden jars, newfangled (at that time) devices that produced electric charges on demand.



Vive Marat (the sign on the left, above) means "Long live Marat." But he didn't have long to live. In 1793, a bloody year in the French Revolution, he was killed by Charlotte Corday as he sat in his bathtub. She hoped to keep his radical party, the Jacobins, from beheading more innocent citizens. Lavoisier was among the thousands of victims during that Reign of Terror.

With all their talent and energy—and the unselfishness of their civic work—the Lavoisiers have legions of admirers, but being part of the government tax system, they also have critics. And Antoine has an enemy with a personal grudge.

His name is Marat—Jean-Paul Marat.

When Marat tries to join the French Academy of Sciences, Lavoisier votes against him because he doesn't think he is a good scientist. Marat is actually a journalist, but he is enraged. This happens just after the American revolutionaries throw out the English king while crying, "No taxation without representation."

The French peasants hear that refrain. France explodes. It is the corruption of the king and his court. It is that tax thing. It is the times. France has a freedom revolution (in 1789).

Then it goes awry (as many revolutions do). Marat becomes a leader in a killing orgy called the Reign of Terror. People—all kinds of people, especially those connected to the king's tax-collection system—are hauled off and killed with the head-chopping machine designed by the kindly Dr. Joseph Guillotin. France loses its way.

Lavoisier loses his head. Science loses a brilliant mind. Marie loses a husband. "It took them only an instant to cut off that head, and a hundred years may not produce another like it," says mathematician Joseph-Louis Lagrange.

Later, the French people erect a statue in Paris in Lavoisier's honor. They are sorry. It is too late; the father of modern chemistry is gone. His ideas survive.

If you want to learn more about the French Revolution—and read one of the best books you will ever read—try Charles Dickens's *A Tale of Two Cities.*