1. Oxygen: The Gas that Changed Everything

CHAPTER 1: What is the World Made Of?

Alignment with the NRC's National Science Education Standards
B: Physical Science
Structure and Properties of Matter:

- An element is composed of a single type of atom.

G: History and Nature of Science
Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Alignment with the Next Generation Science Standards
Science and Engineering Practices
1. Asking Questions and Defining Problems

- Ask questions that arise from examining models or a theory, to clarify and/or seek additional information and relationships.

Re-enactment: In a dank alchemist's laboratory, a white-bearded man works amidst a clutter of vessels, bellows and furnaces.

NARR: One night in 1669, a German alchemist named Hennig Brandt was searching, as he did every night, for a way to make gold.

Brandt lifts a flask of yellow liquid and inspects it.

NARR: For some time, Brandt had focused his research on urine. He was certain the "golden stream" held the key.

Notes from the Field:
I used this section of the program to introduce my students to the concept of atoms. It's a more concrete way to get into the atomic theory.

Notes from the Field:
Humor is a great way to engage my students. Even though they might find a scientist working with his own urine gross and funny, it sure gets their attention!

EVERYDAY APPLICATION 1: Gold has historically been used for decoration and as the basis for currency. Today, gold is even more valuable because of its industrial applications. Gold conducts electricity and resists corrosion, so it is the metal of choice for circuits that require reliability, such as consumer electronics and the Internet. Gold is a catalyst and is used in automobile catalytic converters and in industrial chemical production. Gold is also used in medicines, solar cells, and as a protective coating from radiation and heat.

EVERYDAY APPLICATION 2: Brandt's contemporaries would not have considered him unusual because he investigated urine. During his time people used urine in processes such as cleaning, baking, making beer, preparing wool, and making gunpowder. Urine is still used today as a source of certain medicines. People are also investigating the use of diluted urine as a crop fertilizer because of the elements it contains, including phosphorus.

STOP AND THINK 1: A practice of science is to ask questions that are based on an existing model of how the natural world works. What question was Brandt trying to answer about urine? What theory did Brandt have about gold? What observation about urine led to Brandt's interest in it?

Possible Student Answer: Brandt was trying to determine if urine could be used to make gold. He thought that a substance could be found that could used to make gold. He was interested in urine because of its color.

Brandt places the flask on the forge and moves to another vessel where urine has been heating for some time.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: Tonight his patience would at last be rewarded. He had boiled the urine down to a concentrated paste. Now he subjected it to intense heat.

The vessel begins to glow with an eerie, pale-green light. CU of Brandt's face, his excitement evident.

NARR: Was this the legendary elixir that would turn lead into gold?

Alchemical painting of Brandt in the laboratory, his face lit green by glowing phosphorus. Dissolve to a second alchemy painting.

NARR: Alas, it was not. Brandt had stumbled on the element phosphorus. This is how the discovery of elements began – with people trying to turn the substances of nature into something useful or valuable.

EVERYDAY APPLICATION 3: The property of phosphorus that causes it to glow in the dark for a period of time is called "phosphorescence." People use phosphorescence in several different ways. In biology, phosphorescence is used to identify certain compounds. Phosphorescence is added to paint, which can glow in the dark for minutes or hours after receiving light. Phosphorescent paint is used to mark stairs and ledges in a dark environment such as the theater, to mark dials and numbers on clocks and watches, and to make toys and wall decals glow in the dark.

The host stands behind a table strewn with an assortment of things suggesting the long human tradition of working with materials – rocks, metals, tools, etc. He picks up a rock from the table.

CONCEPT IN BRIEF: element

CONCEPT IN BRIEF: matter

HOST

But people are naturally curious, so as they worked with these materials they began to wonder: What is this stuff? What is the world made of?

On a panel behind the host we see an animation of the ancient Greek philosopher Empedocles and his four elements. The image becomes full screen.

HOST

Thousands of years ago, the Greeks proposed that the world is actually made of just four elements in combination: air, water, earth and fire.

The Periodic Table replaces the four elements on the panel.

HOST

Today we know that matter actually comes in more than 100 distinct varieties, neatly arranged in the Periodic Table of the Elements. But for most of history, matter was a profound mystery – a 2,000-year detective story in which people across the world were trying to identify the elements … and figure out how to use them.

Notes from the Field:

I usually try to connect what we're learning to the historical thinking about that topic—in this case, from the ancient Greeks through the Enlightenment Period. My kids like to see how far things have progressed since then but also how much people actually knew back then.

Composite image of the series' seven main characters

NARR: It's an amazing story, filled with unforgettable characters. In this series, you'll meet seven extraordinary scientists whose findings drove the search for the elements. So join me as we retrace the steps of these "chemical detectives" as they struggle to solve the mystery of matter.

ANNOUNCER: Major funding for *The Mystery of Matter: Search for the Elements* was provided by the National Science Foundation, where discoveries begin. Additional funding provided by the Arthur Vining Davis Foundations – dedicated to strengthening America's future through education. And by the following.

Episode title: Out of Thin Air

CHAPTER 2: The Dabbler: Joseph Priestley

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure and Properties of Matter:

- Solids, liquids, and gases differ in the distances and angles between molecules or atoms and therefore the energy that binds them together. In solids the structure is nearly rigid; in liquids molecules or atoms move around each other but do not move apart; and in gases molecules or atoms move almost independently of each other and are mostly far apart.

G: History and Nature of Science

Nature of Scientific Knowledge

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Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.
- The historical perspective of scientific explanations demonstrates how scientific knowledge changes by evolving over time, almost always building on earlier knowledge.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems
   - Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.
2. Analyzing and Interpreting Data
   - Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.
3. Planning and Carrying Out Investigations
   - Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
   - Select appropriate tools to collect, record, analyze, and evaluate data.

Host in studio. To his left is a panel showing moving images of grass waving in the wind.

HOST

One of the first big clues in solving the mystery of matter came from the discovery of most *immaterial* stuff you can imagine: air.

Images of clouds now appear on the panel.

HOST

Of course, people have always known about air. They could feel the wind on their faces and see its powerful effects in storms. What they didn't know was that there's more than one kind of "air."

STOP AND THINK 2: What do you think the phrase "more than one kind of air" means?

Possible Student Answers: Students may struggle to answer this question, as they may not know how little was understood about substances during the time depicted in the program. Ask students to describe air more scientifically. Once students describe air as "gas" or "mixture of gases," the meaning of the phrase becomes clearer.

Host motions to image of Joseph Black on panel over his other shoulder.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

HOST

That changed in 1754, when a young Scottish medical student named Joseph Black set out to find a cure for kidney stones.

Host pours acid on a chalky substance, releasing some kind of "air." CU of the bubbles formed.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

HOST VO

He poured acid on this chalky substance and trapped the air that came out. To his surprise, this "air" didn't behave like air at all.

He pours the pitcher over a lighted candle, which goes out.

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

HOST

It was heavier than ordinary air – and promptly put out a flame. Black's discovery of "fixed air" – what we now call carbon dioxide – was a turning point in the history of science. People had long known about liquids and solids. Now, suddenly, they realized there was a third state of matter – gases – of which air is just one example. Over the next 20 years, the exploration of this new dimension would transform our understanding of matter.

CONCEPT IN BRIEF: air

CONCEPT IN BRIEF: Scientific knowledge evolves by using new evidence to build on earlier knowledge

Computer graphic combines images of Henry Cavendish and Daniel Rutherford, the names of the elemental gases they discovered and their dates of discovery: hydrogen (1766) and nitrogen (1772).

NARR: After Black's discovery, British scientists quickly identified two more new gases: hydrogen and nitrogen.

STOP AND THINK 3: How did the discoveries of Black, Cavendish, and Rutherford change people's understanding of the make-up of air and of its relationship to liquids and solids?

Possible Student Answers: People had previously thought of air as one substance. Now they understood that air was made of different gases. People also understood that gases were similar to liquids and solids, in that each state of matter was characterized by a variety of substances.

Archival image of Joseph Priestley

HISTORIAN SEYMOUR MAUSKOPF
And then in the early 1770s that astonishing investigator Joseph Priestley discovers all sorts of new "airs."

Footage of Priestley in the lab with his electrical apparatus

NARR: Priestley was a minister by trade, but also an amateur scientist – what was then called a natural philosopher.

BIOGRAPHER STEVEN JOHNSON
He was a great dabbler in things and was constantly getting obsessed with new fields.

Priestley places a glass vessel over a plant.

NARR: Fields like the new science of gases.

In his lab, Priestley continues experimenting with plants and candles under glass vessels. Then he pours acid on a substance to release the "air" it contains. The gas bubbles up in an overturned bottle.

HISTORIAN SEYMOUR MAUSKOPF, partly in VO
Priestley's style of science is very interesting. He's a kind of inspired forager. He's basically messing around with different things to see what will happen. One of the things Priestley did [laugh] was to pour acid on everything. He collected those bubbles, tested them thoroughly and discovered all sorts of amazing properties.

Notes from the Field:
It's important for students to understand that the scientists in this program didn't know about atoms and could only draw conclusions from what they could observe at the macro level.

STOP AND THINK 4: From the narration and images, what did you learn about Priestley's approach to experimentation?

Possible Student Answers: Priestley experimented with many substances, he used specialized equipment to collect the gases, and he developed a number of tests for the gases he collected.

Superimposed on a wide shot of Priestley in the lab the scene is a graphic showing the nine new gases Priestley discovered.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: By "messing around" in this way, Priestley discovered nine new gases – more than anyone else in the world.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

BIOGRAPHER STEVEN JOHNSON, partly in VO

He was very much open to chance discoveries. He would stumble across things, and he would follow his instincts. And he was always looking for these kinds of fortuitous accidents.

Archival image of Leeds

NARR: One such accident happened in 1767, when Priestley was assigned a new congregation.

Archival images of 18th century British breweries

Notes from the Field:

I like to point out circumstances like this where scientific ideas follow coincidence or serendipity rather than a rigid scientific method.

BIOGRAPHER STEVEN JOHNSON, partly in VO

They put him in a house that happens to be right next to a brewery. And this turns out to be an incredible [laugh] stroke of good luck. Priestley, being the kind of constant investigator that he was, would kind of pop over and see what was going on at this brewery.

CONCEPT IN BRIEF: serendipity

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: Just above the vats of beer, he discovered a haze of carbon dioxide bubbling up from the fermenting brew.

BIOGRAPHER STEVEN JOHNSON

And [laugh] he decided he wanted to do some experiments with their beer. Well, fortunately, they said yes.

HOST pours water from one glass to another over a bubbling barrel.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

HOST ON CAMERA

Priestley found that if he simply poured water from one glass to another over the surface, the water would absorb the gas rising from the beer. The result was refreshingly bubbly.

Lab re-enactment of Priestley making soda water. Priestley stops adding acid and vigorously agitates the overturned vessel until the gas is absorbed.

NARR: By 1772, he had invented a better method: generating carbon dioxide and injecting it directly into water.

EVERYDAY APPLICATION 4: Today, carbon dioxide has many commercial uses. It is produced by capturing and purifying byproducts of certain industrial processes. Carbon dioxide is used in welding, to increase production from oil wells, as a source of carbonation in the beverage industry, to prevent fungal and bacterial growth in food products, as a safe propellant in aerosol cans, as a raw material for chemical industry, as a component in fire extinguishing systems, to freeze and refrigerate food products, and in treating the pH of alkaline water.

Words on screen: Words spoken by the characters in this film are drawn from their writings.

JOSEPH PRIESTLEY TO CAMERA

In the space of two or three minutes, I can make a glass of exceedingly pleasant sparkling water. [drinks] You can't tell the difference between this and natural mineral water.

Host behind beer barrel

HOST

Priestley had invented carbonation – remember that the next time you enjoy a soft drink. But with this act he also set in motion a series of improbable events that would soon overturn our understanding of matter.

Priestley agitates his soda water vessel, then takes a sip.

EVERYDAY APPLICATION 5: When carbon dioxide is dissolved into water under pressure, the water becomes carbonated. This process is called carbonation, and it creates the bubbles that so many people enjoy. This process also creates carbonic acid in the drink, which produces a sour taste, or a "bite."

CHAPTER 3: The Portuguese Spy

Alignment with the NRC's National Science Education Standards
F: Science in Personal and Social Perspectives
Science and Technology in Local, National, and Global Challenges

- Progress in science and technology can be affected by social issues and challenges. Funding priorities for specific health problems serve as examples of ways that social issues influence science and technology.

G: History and Nature of Science
Nature of Scientific Knowledge

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- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.
- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

NARR: It began when a British doctor suggested Priestley's "windy water" might be effective as a treatment for scurvy, a disease that plagued sailors on long sea voyages.

Archival image of sailor with scurvy

BIOGRAPHER STEVEN JOHNSON, partly in VO
Scurvy was a huge problem for the military during that period, and so the idea that there was this potential solution that also happened to be a tasty beverage [laugh] was appealing.

EVERYDAY APPLICATION 6: Scurvy is a result of a deficiency in vitamin C in the diet**.** Scurvy is relatively rare today, but does occur in certain populations that have restricted access to fresh fruits and vegetables, such as the elderly and refugees.

Title page of Priestley's paper: Directions for Impregnating Water with Fixed Air

NARR: In 1772, Priestley addressed Britain's leading scientific organization, the Royal Society, and published a pamphlet describing his method for making soda water. He urged the British navy to test the potential cure.

Re-enactment: Magellan picks up the pamphlet and reads it, then begins writing.

NARR: Quick to pick up on this development was a defrocked Portuguese monk named Joao Jacinto de Magellan. A distant relative of the great Portuguese navigator, he was now serving as a French industrial spy.

Magellan seals a package including Priestley's pamphlet.

BIOGRAPHER STEVEN JOHNSON, partly in VO

> Magellan is in the employ of the French government and is there basically scouting out the Royal Society for interesting items that he might be able to bring back to his bosses.

NARR: Sensing a potential military secret …

Cut to Trudaine, reading Magellan's letter, then beginning to write his own. Priestley's pamphlet is alongside.

NARR: … Magellan alerted his handler back in France: Commerce Minister Jean Charles Trudaine de Montigny.

Lavoisier is working in his laboratory when his lab assistant comes in saying (in French) that a letter has arrived from Trudaine. He hands the letter to Lavoisier, who opens the package and begins reading.

HISTORIAN SEYMOUR MAUSKOPF VO

> Trudaine was interested in science, was a member of the French Royal Academy of Sciences, and immediately saw the possible value of this.

NARR: Trudaine, in turn, called on one of France's brightest young chemists, Antoine Laurent Lavoisier.

We hear the first of Trudaine's words in VO, then cut to him on camera writing the letter we're hearing. Occasionally we cut back to Lavoisier reading. He absorbs the meaning of this request. Trudaine delivers the last line to camera, with emphasis.

JEAN CHARLES TRUDAINE DE MONTIGNY, partly in VO

I know your precision when it comes to physics and chemistry, and I'm giving you a chance to be of service to your country. Please repeat these experiments and add your own observations. The value of these discoveries depends on our moving quickly. I hope you will not be long in getting this little work done.

HISTORIAN ALAN ROCKE, partly in VO

Trudaine probably intended this politely phrased letter as an order rather than a request. Lavoisier really couldn't ignore it.

CONCEPT IN BRIEF: Influence of society and culture on science

Lavoisier now opens Priestley's pamphlet and begins to read.

NARR: Though soda water would turn out to be useless against scurvy, this pointed suggestion by a government official, acting on a tip from a Portuguese spy, would set Lavoisier on the path toward his greatest discoveries.

CHAPTER 4: The Thinker: Antoine Lavoisier

Alignment with the NRC's National Science Education Standards

F: Science in Personal and Social Perspectives

Science and Technology in Local, National, and Global Challenges

- Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen. The latter involves human decisions about the use of knowledge.
- Progress in science and technology can be affected by social issues and challenges.

G: History and Nature of Science

Science as a Human Endeavor

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- Ask questions that arise from examining models or a theory, to clarify and/or seek additional information and relationships.
- Ask questions to clarify and refine a model, an explanation, or an engineering problem.

4. Analyzing and Interpreting Data

- Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.

Dissolve to archival image of young Lavoisier

NARR: Born into a well-to-do Parisian family, Lavoisier had received a fine education and taken a degree in law.

Painting of the French court

NARR: Now 28, he had joined a consortium that collected taxes for King Louis the XV.

HISTORIAN SEYMOUR MAUSKOPF VO

As a result, Lavoisier became a very wealthy man.

Laboratory re-enactment: Antoine works in the lab. Cut to Marie Anne elsewhere in the lab.

NARR: But his true passion was chemistry. Lavoisier spent three hours in his private laboratory before work every day, and returned there after dinner … often accompanied by his young wife.

Marie Anne sketches a piece of lab equipment. Her water colors are laid out on the table before her. She calls Antoine, and he comes over to comment on her sketch.

NARR: Marie Anne Paulze was the daughter of one of Lavoisier's business partners.

MARIE ANNE LAVOISIER

Antoine?

ANTOINE LAVOISIER

Oui?

NARR: She was just 13 when they were married … but bright, outgoing and mature beyond her years.

MARIE ANNE LAVOISIER

Lequel est-ce que tu préfères?

Continuing scene, then painting of Antoine and Marie Anne Lavoisier.

HISTORIAN SEYMOUR MAUSKOPF, partly in VO

Marie Anne was virtually his collaborator. She knew English, learned chemistry, assisted Lavoisier in the laboratory. She was an extraordinary person. Had she lived in our own time, she probably would have become an outstanding scientist in her own right.

CONCEPT IN BRIEF: Contributions of individuals and teams to the scientific enterprise

Marie draws an illustration of one of Lavoisier's experiments on respiration, and we see it come to life in a re-enactment.

NARR: One of Marie Anne's most important roles was to create the diagrams and illustrations that accompanied her husband's published work.

HISTORIAN ALAN ROCKE, partly in VO

Marie Lavoisier's drawings give us the eyes to look directly into Lavoisier's laboratory. We can see the people. We can see the devices. We can see the arrangement of those devices. We can understand what Lavoisier did so much better because of what Marie drew.

STOP AND THINK 5: Most scientific discoveries are the result of teams of people working together. How did Marie Anne Lavoisier contribute to the work of Antoine Lavoisier?

Possible Student Answers: Students may respond that Marie Anne Lavoisier participated in discussions about Antoine Lavoisier's work, helped run experiments, kept notes, made illustrations, and helped ensure the communication between French-speaking and English-speaking scientists.

Lavoisier reads a book describing the work of another scientist.

NARR: Spurred on by Trudaine, Lavoisier eagerly studied fresh translations of Black, Priestley and other British chemists who had pioneered the study of "airs."

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

He writes in his notebook.

ANTOINE LAVOISIER, partly in VO

The work of these previous experimenters merely hints at what's happening when air is taken up or released by different substances. I shall review all their work, repeat all their experiments, taking new precautions, in order to develop a coherent theory. This subject, I believe, is destined to bring about a revolution in physics and chemistry.

STOP AND THINK 6: What goals did Lavoisier have in mind when he set out to review and repeat previous experiments investigating air? In what way did his goals differ from Priestley's goals?

Possible Student Answers: Students may know that repetition of a procedure is an important way to confirm that a new discovery or observation has been made. Most importantly, Lavoisier wants to develop a coherent theory to explain the experimental results. Students may suggest that Lavoisier's plan to review other scientists' work and to repeat their experiments will help him to list all known observations and experimental results about gases, which is important because a coherent theory must take into account all known observations and experimental results about gases. Priestley's goals were more experimental in nature—he wanted to discover new gases and develop tests for identifying them.

CHAPTER 5: Phlogiston

Alignment with the NRC's National Science Education Standards

G: History and Nature of Science

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- Select appropriate tools to collect, record, analyze, and evaluate data.

5. Using Mathematics and Computational Thinking
- Use mathematical, computational, and/or algorithmic representations of phenomena or design solutions to describe and/or support claims and/or explanations.

7. Engaging in Argument from Evidence
- Evaluate the claims, evidence, and/or reasoning behind currently accepted explanations or solutions to determine the merits of arguments.

Crosscutting Concepts
- The total amount of energy and matter in closed systems is conserved.

A fire burns in a fireplace. The word PHLOGISTON appears on the screen.

NARR: What made this new science of air so revolutionary was that it threatened to topple the reigning theory of chemistry – a theory inspired by the mystery of fire. Most chemists believed fire was due to some fiery principle that was given up during combustion. And all our senses seem to confirm this idea. Heat, light, smoke – all are *released* as the fire burns. By the mid-1700s, this essence of fire had been given a name: phlogiston.

EVERYDAY APPLICATION 7: Extracting metals from ores and making metal mixtures called alloys is called metallurgy. Many chemical laboratory processes were created and improved in metallurgy long before chemistry existed as a scientific discipline. Archaeological evidence shows that metallurgy began around 8,000 years ago. Metalworking, which is the shaping of metal, began much earlier as some people had access to deposits of pure metal that did not require extraction from ores. Metallurgy is still one of the most important chemical enterprises today, particularly the creation of specialized alloys. Most metals people use are alloys, for example, steel is a mixture of iron with a small amount of carbon.

Image of a rotating bolt, showing both its rusty and its shiny side

NARR: Phlogiston was the foundation of chemistry's leading theory for nearly a century, because it seemed to explain things like metals and rust:

Animation labeled Phlogiston Theory shows that as iron ore is heated alongside charcoal, phlogiston from the charcoal merges with the ore to make metallic iron in the form of an ingot. Then, as a sprinkle of rain falls on the ingot, phlogiston begins leaving the ingot and it turns to rust.

NARR: When iron ore was heated in the presence of charcoal, phlogiston from the charcoal fused with the ore to form metallic iron. When the iron was exposed to air or water, the metal released its phlogiston as it rusted.

In the animation, a copper statue appears alongside the iron, ultimately turning into green verdigris.

NARR: Other metals went through the same process – forming the green verdigris of copper, for example.

Finally, the simple equation appears on the screen, along with the word "calx."

NARR: Ore plus phlogiston equals metal. Metal minus phlogiston equals rust – or what was then called a "calx."

In the animation, a scale is now in place under the iron bar. Paradoxically, it shows that the bar gets heavier as it gives off phlogiston and forms rust, also labeled "calx" in the animation.

HISTORIAN ALAN ROCKE, partly in VO

Only there was a problem: The calx was heavier than the metal, even though phlogiston had left the metal. It's lost something, and yet it was heavier.

ANTOINE LAVOISIER

The calx should weigh *less* than the original metal. But it doesn't. The calx is heavier than the metal.

CONCEPT IN BRIEF: conservation of matter

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

EXAMPLE OF SCIENCE PRACTICE: engaging in argument from evidence

STOP AND THINK 7: Why does Antoine Lavoisier think that the weights of the calx and metal are incompatible with the phlogiston theory?

Possible Student Answers: Students may be able to recall from the narration that the phlogiston theory suggests that phlogiston combines with an ore or calx to form a metal. Therefore, the metal should have gained mass and weigh more than the ore or calx. However, experiments showed that the metal weighed less than the calx.

Lavoisier works at his scale.

HISTORIAN ALAN ROCKE, partly in VO

Though many chemists were aware of this contradiction, they let it pass, because phlogiston otherwise worked so well. But Lavoisier was really troubled by this, because he was obsessed with the weights of his experimental ingredients.

CHEMIST GREGORY PETSKO, partly in VO

Lavoisier was very careful to get very good instruments. He probably, at one point, had the largest and most complete private laboratory on earth.

Lavoisier at the scale

ANTOINE LAVOISIER, partly in VO

With my precision scales, imported from England at great expense, I measure the weight of each substance at the beginning and end of every chemical reaction.

STOP AND THINK 8: Why does Antoine Lavoisier think it is important to precisely measure the weights of each substance at the beginning and end of every chemical reaction?

Possible Student Answers: Students' answers to this question will vary. Students may explain that Lavoisier is verifying which substances break apart or combine. Students may refer to conservation of matter to explain that the weight (or mass) of a closed system will not change even if there is a chemical reaction or physical change. Students may explain that this idea means that atoms are not created or destroyed.

Lavoisier at the scale

HISTORIAN ALAN ROCKE VO

Lavoisier was a master of this balance sheet kind of chemistry. Remember he was tax administrator by day. He knew a lot about accounting. And so this kind of ledger-keeping was natural to him.

CONCEPT IN DETAIL: conservation of matter

EXAMPLE OF SCIENCE PRACTICE: using mathematics and computational thinking

ANTOINE LAVOISIER

It is a fundamental truth of chemistry that the same amount of matter exists before and after each experiment. Nothing new is created, nothing lost. The whole art of performing chemical experiments rests on this principle.

CU of scale and Lavoisier

NARR: Today, we call this idea the Conservation of Matter.

HISTORIAN SEYMOUR MAUSKOPF

When you carry out a chemical reaction, what comes out has to be exactly equal to what goes in.

ANTOINE LAVOISIER

The total weight must remain precisely the same. If not, there's an error somewhere.

Footage of Lavoisier weighing

HISTORIAN ALAN ROCKE, partly in VO

He wasn't the first to assume Conservation of Matter. But Lavoisier applied this idea more rigorously than anyone had before. And it worked very effectively as a tool – a tool of discovery.

CHAPTER 6: The Puzzle of Rust

Alignment with the NRC's National Science Education Standards

G: History and Nature of Science

Science as a Human Endeavor

- Scientists have ethical traditions. Scientists value peer review, truthful reporting about the methods and outcomes of investigations, and making public the results of work. Violations of such norms do occur, but scientists responsible for such violations are censured by their peers.

Nature of Scientific Knowledge

- Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and skepticism, as scientists strive for the best possible explanations about the natural world.
- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public.
- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.
- The historical perspective of scientific explanations demonstrates how scientific knowledge changes by evolving over time, almost always building on earlier knowledge.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems

- Ask questions that arise from examining models or a theory, to clarify and/or seek additional information and relationships.

2. Developing and Using Models

- Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

3. Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

4. Analyzing and Interpreting Data

- Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.

6. Constructing Explanations and Designing Solutions

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena.

Disciplinary Core Ideas

- The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.

Crosscutting Concepts

- The total amount of energy and matter in closed systems is conserved.

Lavoisier uses a spatula to mix a lead calx known as minium with powdered charcoal in a crucible.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: The power of Lavoisier's method would become clear in October 1772, when he set out to solve the riddle of why metals gain weight when they form calxes.

CHEMIST GREGORY PETSKO

Common sense suggested that when things rust they must lose weight. They fall apart. They become brittle and weak. Lavoisier was interested in actually measuring what happened.

Closeups and moves on an engraving of the gigantic double lens that the Academy of Sciences rolled out for a series of experiments in the summer and fall of 1772. CU of the men and women watching in the background.

NARR: He conducted his experiments in public, relying on a huge burning lens that focused the sun's rays to produce intense heat … while elegantly dressed bystanders watched in amazement.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Zoom to crucible showing a mixture of lead and charcoal. The next shot shows Lavoisier marking the water level at the beginning of the experiment, with a small piece of paper glued to the outside of the bell jar.

NARR: Lavoisier placed a calx of lead, mixed with charcoal, inside a glass vessel partially filled with water …

The apparatus is suddenly washed in sunlight, and a narrow beam of light is focused on the crucible under the bell jar. Lavoisier leans down and puts on his sunglasses. The water level rapidly drops below the piece of paper.

NARR: … then subjected it to the intense heat of the burning lens. The result was extraordinary.

ANTOINE LAVOISIER, partly in VO

As the calx changes back into the metal, it releases a large quantity of air. This air forms a volume *a thousand times greater* than the calx it came from.

Footage of Lavoisier watching his experiment, then animation of his proposed explanation.

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

NARR: This startling finding suggested a radical idea: If air came <u>*out*</u> as the calx changed back into a metal, could it have gone <u>*in*</u> when the calx was formed? Could *air* be reason calxes were heavier than expected?

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

STOP AND THINK 9: Lavoisier hypothesized that the additional weight of the calx came from air. What evidence and reasoning supported this hypothesis? What other evidence should Lavoisier try to find to verify his hypothesis?

Possible Student Answers: When the calx was heated, a gas (“air”) was released and the metal appeared. Therefore it makes sense that the reverse process takes place when the calx forms. Two kinds of additional evidence could be collected to support Lavoisier’s hypothesis. He can verify that the same gas that is added to the metal to form the calx is the same gas that is released when the calx is heated. He can heat the metal is the absence of air and verify that the calx is not formed.

Back in the lab, Lavoisier uses the spatula to place yellow sulfur powder in the crucible.

NARR: Lavoisier also found that when he <u>burned</u> elements like sulfur, they, too, gained weight.

CONCEPT IN BRIEF: use of empirical standards, logical arguments, and skepticism to form scientific explanations

ANTOINE LAVOISIER

There was then no doubt. I realized that the increase in weight occurs because a portion of the air is absorbed into the solid material.

Lavoisier makes a final notation in his report on his experiments. Then he seals his note with wax.

CONCEPT IN DETAIL: scientific knowledge evolves by using new evidence to build on earlier knowledge

CHEMIST ROALD HOFFMANN, partly in VO

He knew he was onto something very important. He knew that the element did not lose mass. It gained mass. It *took up* some part of the air.

ANTOINE LAVOISIER, partly in VO

I felt I must secure my right to this important discovery. So I deposited a note with le Secretaire de l'Académie**, to remain sealed until I was ready to make my experiments public.**

EXAMPLE OF SCIENCE PRACTICE: developing and using models

HISTORIAN SEYMOUR MAUSKOPF

He's discovered what seems to be evidence, by weighing things, that seemed to flatly contradict what the phlogiston theory is predicting.

Reprise of rust and fire images

NARR: Despite what our senses tell us, both rusting and burning involve *absorbing* something from the air – just the opposite of what chemistry's reigning theory held.

Continuing shots of Lavoisier at the scale

HISTORIAN ALAN ROCKE, partly in VO

It had been known for a hundred years that metals gain weight when they become calxes. But no one had bothered to really investigate this anomaly. By focusing so intently on weight, Lavoisier had challenged the very foundation of chemistry. And he'd identified the source of that weight gain. Air was somehow involved.

Frustrated by an experiment gone wrong, Lavoisier slams a leaky retort to the ground. It shatters with a loud pop.

NARR: But was it air itself, or some part of the air, and, if so, what part? The identity of the mystery gas eluded him for two years.

STOP AND THINK 10: Although Lavoisier rejected the phlogiston theory, what aspect of that theory does Lavoisier use when he hypothesizes that the same kind of gas reacts with different metals to form calxes?

Possible Student Answers: Students may suggest that Lavoisier believes that one substance is involved in the transformation of differed metals into their respective calxes. The phlogiston theory also proposed this same idea.

Notes from the Field:

This is a good opportunity to show students that scientific work doesn't always go smoothly and can often take a long time.

Marie Anne and Antoine discuss his findings at the dining room table over morning coffee. We hear snippets of their conversation in French.

MARIE ANNE LAVOISIER

Un gaz? Mais lequel?

NARR: He was still stumped in late 1774. But the answer would soon be delivered …

ANTOINE LAVOISIER

Je ne sais pas ….

CHAPTER 7: A Mysterious New Gas

Alignment with the NRC's National Science Education Standards

G: History and Nature of Science

Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.

Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

Asking Questions and Defining Problems

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.
- Ask questions to clarify and refine a model, an explanation, or an engineering problem.

Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

Footage of Priestley in the lab with the red calx of mercury

NARR: … by Joseph Priestley. By this time, Priestley had begun to study something called the red calx of mercury.

CU of liquid mercury on a tabletop

NARR: Mercury is a strange metal – one of just two elements that is liquid at room temperature.

EVERYDAY APPLICATION 8: Mercury is a liquid metal element. It is usually obtained by heating an ore (a compound) called “cinnabar,” which results in the extraction of the mercury. Mercury has many uses because of its unique properties. It is used in some kinds of lamps, thermometers, barometers and manometers (which are devices that measure pressure), electrical switches, battery electrodes, some kinds of paint, and dental fillings.

Pan to reveal its red calx alongside

NARR: But like other metals it forms a calx – a red solid that pharmacists of the 1700s used to treat venereal disease. Chemists had noticed something unusual about this calx.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

Widen out to reveal both mercury and its calx

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: They could convert it back into metallic mercury simply by heating it. No charcoal – no source of phlogiston – was needed.

Priestley gazes out a window.

NARR: This was theoretically impossible. How could it be?

Priestley continues his experiment with mercury calx. He places a sample of (fake) mercuric oxide in a glass retort, then uses his burning lens to focus a spot of sunlight on the sample of mercuric oxide. The red powder begins to turn black. Gas bubbles up in his pneumatic trough, displacing the water in an overturned receiving vessel.

NARR: The ever-curious Priestley wanted to know. So in August 1774, he obtained a sample of mercury calx and used his own burning lens to heat it with sunlight.

CHEMIST ROALD HOFFMANN, partly in VO

That reddish substance in turn decomposes, giving back mercury, but also a gas.

When the gas has driven all the water out of the vessel, he slides a plate under the vessel and moves it to another part of his workbench. He lifts it slightly to insert a lighted candle, expecting it to go out. Instead, to his surprise, the candle burns bigger and brighter than the candle alongside in ordinary air.

HISTORIAN SEYMOUR MAUSKOPF VO

Priestley collects this air, because he likes to test these gases to see what properties they have.

NARR: If it were his old friend "fixed air," the candle would go out.

HISTORIAN SEYMOUR MAUSKOPF VO

But what he found about this air was that it had quite extraordinary properties.

Priestley leans down to examine the two candles. One is out, while the one in the new air continues to burn brightly.

JOSEPH PRIESTLEY, partly in VO

What astounded me was that the candle burned in this air with remarkable vigor. The flame was bigger and brighter than in ordinary air.

BIOGRAPHER STEVEN JOHNSON VO

Something in this air seems almost better than normal air, which is very puzzling.

Priestley inserts a piece of "red hot wood" into the vessel. It bursts into flame. He stoops down to look at it, astonished.

JOSEPH PRIESTLEY, partly in VO

I was utterly at a loss. How could I explain this?

STOP AND THINK 11: Describe the main difference between this new gas and the “fixed air” Priestley was already familiar with.

Possible Student Answers: The new gas increased combustion while the fixed air decreased combustion.

CHAPTER 8: A Fateful Dinner

Alignment with the NRC’s National Science Education Standards

G: History and Nature of Science

Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.

- Scientists have ethical traditions. Scientists value peer review, truthful reporting about the methods and outcomes of investigations, and making public the results of work. Violations of such norms do occur, but scientists responsible for such violations are censured by their peers.
- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Historical Perspectives

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Alignment with the Next Generation Science Standards

Science and Engineering Practices

8. Obtaining, Evaluating, and Communicating Information

- Gather, read, and evaluate scientific and/or technical information from multiple authoritative sources, assessing the evidence and usefulness of each source.

Cut to re-enactment of Paris dinner with Antoine and Marie Lavoisier and other French scientists. While others are chattering away in French, Madame Lavoisier makes a special point of speaking to him in English, in which she (unlike Antoine) is fluent.

JEAN CHARLES TRUDAINE DE MONTIGNY

Buvons à la santé d'Archimède!

MARIE ANNE LAVOISIER

Dr. Priestley, have you been to the Continent before?

JOSEPH PRIESTLEY

No, this is my first time.

NARR: Two months later, on a visit to Paris, Priestley was invited to dine with members of the Royal Academy of Sciences … including Antoine Lavoisier.

STOP AND THINK 12: This dinner is an example of a characteristic type of event for this time, in which people would meet in private and public places to freely exchange their thoughts about different issues in the arts and sciences. How might discussions and debates lead to the creation of new ideas?

Possible Student Answers: Students' answers to this question will vary. Students may explain how discussions and debates can cause people to rethink their ideas because they gain new information and learn about new perspectives.

CONCEPT IN BRIEF: contributions of individuals and teams to the scientific enterprise

Dinner scene continues.

JOSEPH PRIESTLEY

J'ai récemment réalisé …

HISTORIAN SEYMOUR MAUSKOPF, partly in VO

Priestley tells Lavoisier in his very broken French about his new discovery.

JOSEPH PRIESTLEY

… avec les résultats tres intéressants.

Dinner scene continues, bits of conversation intercut with Priestley and scholar bites.

JOSEPH PRIESTLEY, partly in VO

I described this experiment at the table of Monsieur Lavoisier. I never make the least secret of anything that I do.

JOSEPH PRIESTLEY

… la même aire de plombe rouge.

BIOGRAPHER STEVEN JOHNSON, partly in VO

Everything that he came up with, every new experiment that he did, even when he wasn't sure what the results meant …

JOSEPH MACQUER

Que est-ce que se ce plombe rouge?

BIOGRAPHER STEVEN JOHNSON, partly in VO
… he was constantly sharing that information with as many people as possible.

JOSEPH PRIESTLEY
Mais à ma grande surprise …

JOSEPH PRIESTLEY VO CONTINUES
I also told them that it produced a kind of air in which a candle burned much better than in common air.

JOSEPH PRIESTLEY
… mieux que dans l'air commun.

The men and women around the table, including Antoine and Marie Anne Lavoisier, exchange surprised glances. "Mieux?"

JOSEPH PRIESTLEY, partly in VO
At this the entire company – including Monsieur and Madame Lavoisier – expressed great surprise. I'm sure they cannot have forgotten these events.

Intrigued, Antoine questions Priestley intently, with Marie Anne translating.

ANTOINE LAVOISIER
Monsieur Priestley, etes-vous bien sûr que ce n'était pas l'air fixe?

MARIE ANNE LAVOISIER
If you want, I can translate for you.

JOSEPH PRIESTLEY
Aha. Merci.

MARIE ANNE LAVOISIER
Are you sure that what you found was not fixed air?

JOSEPH PRIESTLEY
Absolutely. But I'm not yet sure what it was.

STOP AND THINK 13: One of Priestley's characteristics was his willingness to share his work. Why is it important to communicate experimental results in science?

Possible Student Answers: Students may suggest that the addition of relevant knowledge from each other can allow scientists to better analyze and advance their own work.

Dinner scene continues.

HISTORIAN SEYMOUR MAUSKOPF, partly in VO
Lavoisier did not appreciate Priestley's style. He didn't think Priestley brought very much thought to his scientific foraging.

Lavoisier listening intently

BIOGRAPHER STEVEN JOHNSON, partly in VO
But Lavoisier was smart enough to recognize that Priestley was onto something and take that piece of information and go back to his lab to figure out exactly what Priestley had discovered.

Lavoisier and his assistant leave the lab.

NARR: Could this be the gas he was looking for – the one involved in rusting and burning? Lavoisier hurried to the local apothecary to buy his own sample of mercury calx.

CHAPTER 9: Oxygen

Alignment with the NRC's National Science Education Standards
G: History and Nature of Science
Science as a Human Endeavor

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Alignment with the Next Generation Science Standards

Science and Engineering Practices

Asking Questions and Defining Problems

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.

Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

Re-enactment: Priestley uses his electrostatic generator to amuse his eight-year-old son.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: Back in England, Priestley dithered for months on other projects, unaware he was in danger of being scooped.

JOSEPH PRIESTLEY (to son)

Look what you can do.

A thought occurs to Priestley as he wipes out a glass vessel.

NARR: Finally, it occurred to him: If this gas he had discovered supports fire, might it also support breathing?

He pulls a mouse out of its cage and places it under a bell jar. Priestley jots down a note while watching the mouse closely.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

BIOGRAPHER STEVEN JOHNSON, partly in VO
Here we have one of the great discoveries in the history of chemistry, and the scene is kind of amazing. You've got this man and a mouse [laugh].

JOSEPH PRIESTLEY, mostly in VO
I put a mouse into a glass vessel containing two ounces of the air from the heated calx of mercury. If it were common air, a full-grown mouse would have survived in it perhaps a quarter of an hour.

Close-ups of the mouse – perfectly comfortable as time passes

BIOGRAPHER STEVEN JOHNSON VO
15 minutes pass … 20 minutes pass.

Priestley consults his pocket watch to see how much time has passed.

JOSEPH PRIESTLEY
In this air, my mouse remained perfectly at ease for a full half hour.

Close-up of the frisky mouse

BIOGRAPHER STEVEN JOHNSON VO
That's twice as long as any mouse has ever survived.

He removes the mouse, which seems none the worse for wear.

JOSEPH PRIESTLEY, beginning in VO, ending OC
I began to suspect that the air into which I had put the mouse was *better* than common air.

Now Priestley puts the mouse back under glass in the same air it has just breathed for half an hour.

BIOGRAPHER STEVEN JOHNSON, partly in VO
He takes the same mouse and sticks it back under the glass and, sure enough, the mouse survives another 30 minutes in this strange new air.

Notes from the Field:
Although my students got a chuckle out of Priestley inhaling the gas, I took the chance to make a comparison between our lab safety rules now and what was done back then.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Priestley stoops down and smiles as the mouse grooms itself.

BIOGRAPHER STEVEN JOHNSON VO

He realizes that something fundamentally different has happened. This air is some kind of super air.

Priestley watches the mouse.

JOSEPH PRIESTLEY, partly in VO

I concluded that this air was between five and six times better – that is, more breathable – than the best common air I'd ever tested.

He removes it from under the jar.

BIOGRAPHER STEVEN JOHNSON, partly in VO

He finally has kind of convinced himself this air must be safe to breathe if the mouse is doing so well. And so he gets up enough courage to actually try it himself.

Priestley holds a tube up to his mouth, breathes in some of the gas, stops to consider the sensation, and then talks to camera.

JOSEPH PRIESTLEY

It doesn't feel any different from common air when I breathe it in. But I feel peculiarly light and easy. In time, this pure air may be useful as a medicine or sold to the fashionable for recreation. Up to now, only two mice and I have had the privilege of breathing it.

Antoine and Marie Anne in the Paris lab perform their own experiments on this new air. He removes the vessel from the trough and takes it to testing area. He inserts the lit candle, which leaps up and burns brightly.

BIOGRAPHER STEVEN JOHNSON VO

As Priestley is conducting these experiments in England, across the channel, Lavoisier is basically going through the exact same experiments.

STOP AND THINK 14: Sometimes scientists are in competition with each other to make a discovery or find an important technological application. What are the pros and cons of competition among scientists?

Possible Student Answers: Students may say that competition makes scientists work harder but that there may be duplication of effort.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

CHEMIST ROALD HOFFMANN, partly in VO

Lavoisier, realizing that this is essentially the key to the mystery, gets to work on it.

Charcoal throws out sparks. Antoine and Marie Anne laugh at the sight.

ANTOINE LAVOISIER, partly in VO

I found – much to my surprise – that this air had none of the properties of "fixed air." A candle burned in it with a dazzling splendor; and charcoal, instead of just smoldering, threw sparks in every direction.

Painting of the Academy building

NARR: Lavoisier announced his findings with great fanfare at the 1775 Easter meeting of the Academy of Sciences.

ANTOINE LAVOISIER, partly in VO

All this evidence convinced me that this air is more … [searching for words] breathable – more combustible – and more pure than even the common air in which we live.

BIOGRAPHER STEVEN JOHNSON

And he gives it the name oxygen.

EVERYDAY APPLICATION 8: Today, oxygen has many commercial uses. It is produced by purification from air and is used in the steel industry, in sewage and waste incineration, in rocket fuel, in submarines and diving bells, in chemical and ceramics manufacture, in medical oxygen tents and pediatric incubators, and in gaseous anesthetics.

Reprise dinner scene

NARR: In announcing his findings, Lavoisier made no mention of Priestley's revelation over dinner six months earlier.

> Notes from the Field:
> I had my class discuss how Priestley and Lavoisier's work compares, the sharing of new findings, and ethics in science.

CHEMIST ROALD HOFFMANN, partly in VO

Now, Priestley is not a shrinking violet here. He hears about this, and he objects.

JOSEPH PRIESTLEY

He should have acknowledged the fact that my account over dinner led him to try the experiment. One should not put one's scythe into another man's harvest.

ANTOINE LAVOISIER

I admit I was not the first to do these experiments. That claim goes to Mr. Priestley. But from the results we have drawn diametrically opposite conclusions.

I may be criticized for having borrowed from the work of this celebrated philosopher, but I trust that the originality of my conclusions will not be challenged.

> **STOP AND THINK 15:** Priestley states that Lavoisier should have acknowledged his role in the discovery of oxygen. Do you think that Lavoisier should have done this? Why or why not?
>
> **Possible Student Answers:** Students' answers to this question will vary. Some students may feel that Lavoisier should have acknowledged Priestley's work while others may think differently. You may want to follow up with a question about what Priestley might have done to ensure that his work was both shared and publically acknowledged.

CHAPTER 10: The Chemical Revolution

Alignment with the NRC's National Science Education Standards
G: History and Nature of Science
Science as a Human Endeavor

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Alignment with the Next Generation Science Standards
Science and Engineering Practices
Developing and Using Models

- Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

Lavoisier in lab re-enactment scenes

NARR: Lavoisier was right. While it was Priestley who made the discovery, it was Lavoisier who grasped the implications of this new gas.

CHEMIST ROALD HOFFMANN, partly in VO

Lavoisier was the only one who understood what was going on. Perhaps he didn't understand perfectly but the moment that new element, which we call oxygen, was there, he picks it up and he runs with it.

Lavoisier writes. Then an image of the atmosphere, with the names of its constituents – nitrogen and oxygen – superimposed.

NARR: Over the next 15 years, Lavoisier would show that air is not a simple substance, as the ancients believed, but a mixture of two newly discovered gases …

Image of water with its constituents overlaid: hydrogen and oxygen

NARR: … that water, too, was a product of two gases ...

Footage of a candle burning

NARR: … and that fire is not an element but a *process* of combining with oxygen.

Image of cliffs of earth

NARR: Even the solid substances the ancients had lumped under the heading "earth" were now seen in a new way.

Blacksmith painting. Shots of a copper ore and metallic copper behind it.

HISTORIAN ALAN ROCKE, partly in VO

Metals like iron and tin and lead had been known for centuries. But in the era of phlogiston they were thought to be compounds, because they had phlogiston in them. Lavoisier had turned this picture upside down. He showed that by stripping away the oxygen from the ore, you got down to the simpler metal within. The metal, not the ore, was the element.

CONCEPT IN DETAIL: element

The four previous images now fill the four quadrants of the screen, and "O" appears in the center.

NARR: So all four of the ancient elements – air, water, earth and fire – had been abolished, thanks to the discovery of oxygen.

CONCEPT IN DETAIL: scientific knowledge evolves by using new evidence to build on earlier knowledge

EXAMPLE OF SCIENCE PRACTICE: developing and using models

ANTOINE LAVOISIER

Once you accept the existence of oxygen, the main difficulties of chemistry appear to evaporate. Well, if all of chemistry can be explained without phlogiston, in all likelihood it doesn't exist.

Priestley pours water in his lab.

NARR: For years, many chemists – including Joseph Priestley – refused to abandon the old theory.

Title page of Traite Elementaire de Chimie

NARR: What finally won the day was the textbook Lavoisier wrote in 1789 to spread his new chemical theory. As it was adopted around the world, phlogiston quietly passed into history.

HISTORIAN SEYMOUR MAUSKOPF
So the old chemical system has been essentially destroyed.

Footage of Lavoisier at his scale, Priestley with his mouse

NARR: Though Lavoisier is often given most of the credit, it was really both these men, working in their very different ways, who brought about this Chemical Revolution.

Priestley shakes his soda water bottle.

BIOGRAPHER STEVEN JOHNSON, partly in VO
They kind of needed each other in a way. For science to work you need both kinds of scientists, right? You need the scientists who are great systematizers, and then you need the mavericks and the tinkerers who are going to open up new doors for discovery.

CONCEPT IN DETAIL: contributions of individuals and teams to the scientific enterprise

The two men look out their respective windows.

NARR: One of the doors Priestley and Lavoisier opened was a fresh way to tackle that old question: What is the world made of?

Reprise shot of copper ore and metal

NARR: It was clear now that rocks of every conceivable variety might harbor undiscovered elements chemically fused with oxygen.

CHEMIST GREGORY PETSKO

People realized that if they could release oxygen from other substances, what was left behind might be some of these missing elements that everybody knew must be out there.

CONCEPT IN DETAIL: element

CONCEPT IN DETAIL: matter

HISTORIAN ALAN ROCKE

How many more elements might you find by stripping away the oxygen that like to bind to so many things?

Pan up list of "simple substances" in Lavoisier's book.

NARR: Lavoisier's textbook included the first modern list of elements – 33 "simple substances."

CU of "lumière" on Lavoisier's list

NARR: Some, including light and heat, were later found not to be elements. But it was a start, and it served as a challenge to other chemists.

HISTORIAN ALAN ROCKE

Now that they knew how to look for them, chemists began to ask: What *are* the elements? The question had never been asked before in exactly that way. And so the discovery of oxygen really served as a starting gun for a worldwide race for new elements.

ACTIVITY IDEAS

Priestley and Soda Pop

Reference: http://www.chemheritage.org/discover/online-resources/chemistry-in-history/activities/priestley-and-soda-pop.aspx

Students learn about a method of producing carbon dioxide similar to the one Priestley used, and they then measure the volume of the gas that they can recover from a definite volume of carbonated beverage.

Distinguish Between Carbon Dioxide and Oxygen

Reference: http://mattson.creighton.edu/MysteryGas/Mystery_Gas.html

Make carbon dioxide and oxygen, and ask students to design and carry out reasonable tests that would help them distinguish between these two colorless gases.

Demonstrate Photosynthesis

One of the outcomes of the experiments of Priestley and Lavoisier was an understanding that animals use up oxygen and produce carbon dioxide, and that plants use up carbon dioxide and produce oxygen. The first process is called respiration and the second process is called photosynthesis. In this activity, demonstrate or have students view the oxygen that is released in photosynthesis by using a household aquarium water plant called elodea. Carry out the following steps:

1. Collect a sprig of elodea, scissors, water, a test tube, baking soda, ¼ teaspoon measurer, a 100-mL beaker, and a heat lamp.
2. Cut the stem of the sprig of elodea at an angle so you can see the cross-section of the stem.
3. Place the sprig of elodea into a test tube.
4. Add ¼ teaspoon of baking soda to the test tube.
5. Place the tube into a beaker filled with water.
6. Place the beaker and test tube under a heat lamp.
7. Wait 5 minutes and then periodically observe the cut surface of the elodea stem to see if the elodea is producing oxygen gas. The oxygen gas will bubble up to the surface of the test tube.

TEACHER NOTES

IN-DEPTH INVESTIGATION: BACK TO THE 1700S

Context

In *Oxygen: The Gas that Changed Everything*, the scientists Joseph Priestley and Antoine Laurent Lavoisier are profiled. These two scientists were both very skilled in the laboratory, but otherwise had different strengths. Priestley was curious, creative, and could interpret unusual laboratory results. Lavoisier was logical, analytical, and could propose coherent theories that connected disparate observations. The exchange of views between these two scientists, one based in England and one in France, led to the formation of some of the most important ideas in chemistry.

Overview

Students read how experimentation with gases and calxes in the 1700s helped provide a foundation for the science of chemistry. Students then investigate the reaction of steel wool with oxygen in the air, using vinegar to remove the protective coating on the steel and to speed up the reaction. To prepare for the investigation, students discuss their ideas about the role of gases in this reaction and then propose specific techniques that they will use to study the role of gases in the reaction. *Note: You may want students to begin the reaction first and then complete the reading, as the reaction time is lengthy.*

Next Generation Science Standards Alignment

Science and Engineering Practices

1. Asking Questions and Defining Problems
    - Ask questions that arise from careful observation of phenomena to seek additional information.
5. Using Mathematics and Computational Thinking
    - Use mathematical representations of phenomena to support claims and explanations.
6. Constructing Explanations and Designing Solutions
    - Apply scientific principles and evidence to provide an explanation of phenomena.

Disciplinary Core Ideas

- The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.

Crosscutting Concepts

- The total amount of energy and matter in closed systems is conserved.

Understanding Goals

Students should understand:

- Air is a homogeneous mixture of gases that is composed of nitrogen, oxygen, carbon dioxide, and argon.
- An element is a substance that cannot be further broken down.

- Compounds are substances that can be broken down into elements.
- Compounds often have very different properties than their constituent elements.
- Chemical changes are often indicated by one or more of the following: color change, gas evolution, precipitate formation, evolution of light, temperature change, or a change in smell/taste.
- In any chemical reaction, mass is conserved. For a closed system, the mass of the reactants equals the mass of the products (law of conservation of mass).

Student Materials

You will find on the following pages a reading and instructions for conducting a laboratory experiment.

Laboratory Experiment Facilitation

- Circulate around to students as they work on the experiment.
- Review the concepts of claim, reasoning, and evidence.

Notes from the Field:

I extended this activity by having students test different grades of steel wool. Or you could repeat the tests on other materials made of different elements.

Laboratory Experiment Rubric

Criteria	Not evident	Limited	Developing	Competent	Accomplished
Carefully follow procedure steps and safety rules, and record observations and data	Did not complete the experiment	Did not follow procedure steps and/or safety rules	Carefully followed procedure steps and safety rules, but did not record observations and data	Carefully followed procedure steps and safety rules, and partially recorded observations and data	Carefully followed procedure steps and safety rules, and fully recorded observations and data
Use evidence of change in mass to support claim that air is involved in the reaction	No claim	Claim made, but explanation did not refer to change in mass	Claim made and explanation referred to change in mass, but the reasoning that linked claim and	Claim made and explanation referred to change in mass, and reasoning that linked claim and evidence	Claim made and explanation referred to change in mass, and reasoning that linked claim and evidence

			evidence was not convincing	was somewhat convincing	was completely convincing
Seek additional data about reaction and describe an experiment to gather that data	No additional data sought	Additional data sought provided no new data	Additional data sought provided new data, but no experiment was suggested	Additional data sought provided new data, but suggested experiment would not gather that data	Additional data sought provided new data, and suggested experiment would gather that data

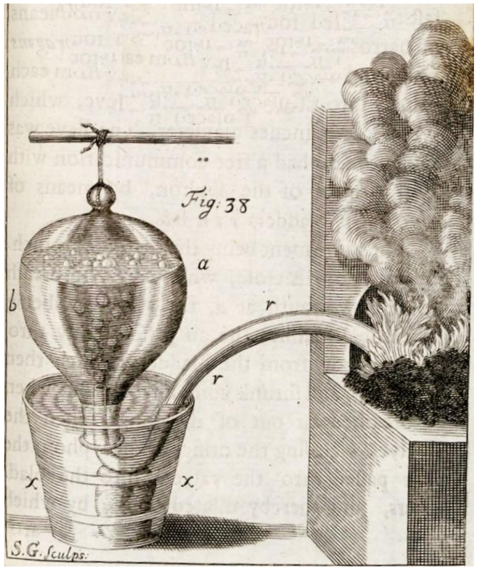
IN-DEPTH INVESTIGATION: BACK TO THE 1700S

READING: Gases and Calxes: Experiments that Launched Modern Chemistry

The modern science of chemistry began in the 1700s, when investigations by various scientists led to several important ideas that would define chemistry as a scientific discipline. Many of these ideas came about when scientists studied gases and calxes. Calxes are the ashy or powdery substance that remains when a metal has been subjected to combustion by heat. Some of the scientists who engaged in these experiments were Stephen Hales (1677–1761), Joseph Black (1728–1799), Henry Cavendish (1731–1810), Joseph Priestley (1733–1804), Karl Wilhelm Scheele (1742–1786), Antoine Laurent Lavoisier (1743–1794), and Daniel Rutherford (1749–1819).

Experiments with Gases

Many scientists in the 1700s studied gases. Stephen Hales paved the way by developing a method to collect gases. If a reaction produced a gas, he ran a tube from the reaction into an upside-down container filled with water. The upside-down container was placed inside a larger container, or trough, that was also filled with water. When gas came through the tube, it bubbled to the top of the upside-down container and pushed down, or displaced, the water in the trough. Refer to Figure 1. This method is called the water displacement method and it is still commonly used today.



Source: http://en.wikipedia.org/wiki/File:Hales_Stephen_trough.jpg

Figure 1: *This is a drawing by Stephen Hales that shows his new method for collecting gas from a reaction. Once the upside-down container was completely filled with gas, it could be quickly turned right-side up and stoppered. This method is often called the water displacement method.*

Using the water displacement method, Joseph Black discovered carbon dioxide, Henry Cavendish discovered hydrogen, and Joseph Priestley discovered more gases than anyone else in history. His discoveries included the gases nitrogen dioxide, nitrous oxide (laughing gas), nitric oxide, anhydrous hydrochloric acid, carbon monoxide, ammonia, oxygen, sulfur dioxide (this is the gas released by onions that makes you cry), and silicon tetrafluoride. One reason that Priestley discovered so many gases was that he modified Hales' method. Some gases dissolve in water and could not be collected by displacing water. Priestley solved this problem by bubbling water-soluble gases through mercury, a liquid metal.

When a scientist isolated a gas from a reaction, the gas had to be identified by testing its properties. Because most gases are colorless, scientists could not always rely on sight and had to find different ways to test the gases. Some of the tests included smell, the ability to support combustion, flammability, and ability to support animal life. By carrying out these tests, scientists determined that there were different gases with distinct properties and that air was a mixture of gases.

Experiments with Calxes

In related work, many scientists in the 1700s studied calxes. Heating up a metal resulted in the formation of a new substance that was ashy or powdery, and these substances were collectively called calxes. Measurements of weight established that a calx was heavier than the starting weight of the metal that formed it.

Scientists tried to understand what occurred during the calx-making process. Antoine Lavoisier was able to bring the most clarity to the reaction. He took careful measurements of weight while carrying out the calx reaction in a closed reaction chamber. He found that the total weight to the reaction system did not change. He then opened the closed reaction chamber and observed that air rushed into it. He then measured the weight of the calx and found that it had increased in weight when compared to the starting material, as expected. By a series of careful measurements, Lavoisier determined that the weight of the air that rushed into the closed reaction chamber exactly equaled the increase of weight of the calx.

Lavoisier concluded from these results that the metal reacted with some portion of the air during the calx-making process. He made further measurements by using water to replace the amount of air that was used up in the reaction. He found that the portion of the air that reacted with the calx was 20% of the volume of air. However, he did not know exactly what part of the air was reacting with the metal during the calx-making process.

However, in addition to making calxes, Lavoisier, Priestley, and other scientists would also decompose them. They knew that the original metal could be obtained from a calx by heating it to a higher temperature than the temperature that was used to make it. A gas was also produced during a decomposition reaction. Joseph Priestley carried out a decomposition reaction of a calx of mercury and isolated the gas that was produced. He found that this gas was oxygen, which supported combustion and life. During a visit to Paris, Priestley communicated his results to Lavoisier, who realized that oxygen must be the gas that was reacting with the metal during the calx-making process. He concluded that the decomposition of calxes was the reverse of the formation of calxes.

By considering the results of his and others' experiments, Lavoisier was able to propose several important ideas that would help launch modern chemistry. These ideas were:

- Matter was made up of substances, each of which had their own identity and properties.
- Substances could be elements or compounds.
- Compounds could be broken down by chemical reaction into elements while elements could not be broken down.
- Weight (mass) was conserved if a system was kept contained or closed during a chemical change or reaction. This idea is now called the Law of Conservation of Mass.

LABORATORY EXPERIMENT: Reaction with Air?

Heating metals to high temperatures produced calxes. However, Priestley observed that iron could form a calx by being exposed to water steam, which is not that hot. The iron calx is also called “rust.” Another way to form rust without heating the iron is to expose the iron first to acid and then to air. The acid removes any coating on the metal and speeds up the reaction with air. In this investigation, you will place iron in vinegar, a weak acid, and then allow the iron to react with air at room temperature. During the reaction with air, you will use techniques similar to those used by Lavoisier to determine what happens during the calx-forming process.

Materials

- gloves
- safety glasses
- aprons
- super-fine steel wool (found in paint stores or hardware stores)
- forceps
- 250-mL beaker
- paper towels
- 250-mL flask
- white vinegar
- balloon
- balance

Discussion

Discuss the following with your group and be prepared to share your answers with the whole class.

1. Steel wool is made mainly of iron. Predict what will happen when the iron in the steel wool is first exposed to a weak acid and then to the air.
2. Predict how the weight or mass of the calx made from the steel wool will compare with the weight or mass of the steel wool at the beginning of the reaction.
3. Will air be involved in the reaction that forms the calx from the steel wool? Why or why not?
4. When Lavoisier examined the calx-making process, he used two important techniques to help him determine what happened in the reaction. These two techniques were the measurement of weight and closing the reaction system. Examine the materials for this investigation and propose how you would carry out these same techniques.

Procedure

Carry out the following steps with your group and record all work in your notebook.

1. Put on gloves and safety glasses.

2. Carefully observe the steel wool and feel its texture. Record your observations.
3. Use the forceps to tear off an egg-sized piece of steel wool.
4. Use the forceps to place the steel wool into the 250-mL beaker.
5. Add white vinegar to the 250-mL beaker until the entire piece of steel wool is immersed.
6. Wait 4–7 minutes.
7. Spread out 3 layers of paper towels.
8. Use the forceps to remove the steel wool from the vinegar and place on the paper towels.
9. Use additional paper towels to wring out any excess vinegar.
10. Use the forceps to place the steel wool into the 250 mL flask.
11. Cover the opening of the 250-mL flask with a balloon.
12. Measure the mass of the entire steel wool-balloon-flask system and record.
13. Allow this system to sit for 30-45 minutes.
14. Observe the steel wool-balloon-flask system and record your observations.
15. Measure the mass of the entire steel wool-balloon-flask system and record.
16. Remove the balloon slowly and record your observations.
17. Use the forceps to remove the steel wool and place on a paper towel.
18. Carefully observe the steel wool and feel its texture. Record your observations.
19. With your group, develop an explanation about what you think occurred in this reaction.
20. Share your ideas with the whole class.

Questions

1. What is the common name of the calx that formed on the steel wool?
2. Was air involved in this reaction? Explain the evidence that you used to answer this question.
3. What additional data could you gather that would help you determine what happened in this reaction? What experiment would you do to gather the data?

TEACHER NOTES

IN-DEPTH INVESTIGATION: THEORIES OF COMBUSTION

Context

A change in the understanding of the nature of matter occurred during the 1700s. Alchemical ideas based on transformative principles were becoming less useful. New ideas gaining acceptance included conservation of mass and the idea that matter could be viewed as building blocks. The competing theories of phlogiston and oxygen described in *Oxygen: The Gas That Changed Everything* reflect this change in understanding. Antoine-Laurent Lavoisier challenged the alchemical theory that combustion was caused by phlogiston. He proposed that combustion was caused by the combination of a substance with oxygen in the air, an explanation consistent with experimental evidence.

Overview

Students read about the theories of phlogiston and oxygen, Dalton's atomic theory, and the mole. Students examine data from a reaction between magnesium and oxygen and carry out the following three tasks:

- Students explain how the data supports the theory of oxygen.
- Students use moles to determine the ratio of atoms in the compound produced in the reaction.
- Students explain if the data shows that mass and atoms are conserved in the reaction.

Next Generation Science Standards Alignment

Science and Engineering Practices

2. Developing and Using Models
    - Evaluate merits of two different models of the same proposed process in order to select a model that best fits the evidence.
5. Using Mathematics and Computational Thinking
    - Use mathematical representations of phenomena to describe and support claims and explanations.
6. Constructing Explanations and Designing Solutions
    - Apply scientific principles and evidence to provide an explanation of phenomena.
7. Engaging in Argument from Evidence
    - Evaluate the evidence and reasoning behind currently accepted explanations to determine the merits of arguments.

Core Ideas

- The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.

Crosscutting Concepts

- The total amount of energy and matter in closed systems is conserved.

Performance Expectations

- Chemical Reactions HS-PS1-7: Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.

Understanding Goals

Students should understand:

- All matter is composed of very small particles called atoms.
- Particles of matter move differently in the gas, liquid, and solid states.
- The atoms of each element have the same characteristics and weight, but different characteristics and weight from atoms of other elements.
- Atoms of one element can combine with atoms of another element, resulting in different compounds.
- Atoms are indivisible and unchanging. Therefore, atoms do no change even when combined with other atoms, and the combination of atoms occurs in small, whole-number ratios such as 1:1 or 1:2.
- The mole is a dimensionless unit equal to 6.022×10^{23}.
- The mass of a mole of identical atoms has the same numerical value as the mass of that atom in atomic mass units.
- The mass of a mole of identical groups of atoms in grams has the same numerical value as the mass of a single group of atoms in atomic mass units.
- The ratio of moles is equal to the ratio of atoms or groups of atoms.
- In any chemical reaction, mass and atoms are conserved. For a closed system, the mass and atoms of the reactants equal the mass and atoms of the products.

Student Materials

You will find on the following pages a reading and activity.

Activity Facilitation

- Review the mole concept if it is unfamiliar to your students. Then specifically review how to find the mass of one mole of magnesium and oxygen using the Periodic Table.
- Circulate around to students as they work on the activity.
- Calculations for determining the number of grams and the number of moles of magnesium and oxygen follow.
  - The mass of magnesium = 21.87 g – 19.65 g = 2.22 g
  - The mass of the product = 23.38 g – 19.65 g = 3.73 g
  - The mass of the added oxygen = 3.73 g – 2.22 g = 1.51 g
  - The number of moles of magnesium (Mg) = 2.22 g ÷ 24 g/mol = 0.092 mol
  - The number of moles of oxygen (O) = 1.51 g ÷ 16 g/mol = 0.094 mol
- Review the concepts of theory, claim, evidence, and reasoning

Activity Rubric

Criteria	**Not evident**	**Limited**	**Developing**	**Competent**	**Accomplished**
Evaluate which combustion theory was supported by evidence of change in mass	No explanation	Theory chosen, but explanation did not refer to change in mass	Theory chosen and explanation referred to change in mass, but the reasoning that linked theory and evidence was not convincing	Theory chosen and explanation referred to change in mass, and the reasoning that linked theory and evidence was somewhat convincing	Theory chosen and explanation referred to change in mass, and the reasoning that linked theory and evidence was completely convincing
Mole calculations and chemical formula	No mole calculations	Mole calculations mostly incorrect	Mole calculations and chemical formula somewhat correct	Mole calculations and chemical formula mostly correct	Mole calculations and chemical formula completely correct
Evaluate how mass data support Dalton's theory of atoms	No explanation	Explanation did not refer to whole number ratios	Explanation referred to whole number ratios, but the reasoning that linked theory and evidence was not convincing	Explanation referred to whole number ratios, and the reasoning that linked theory and evidence was somewhat convincing	Explanation referred to whole number ratios, and the reasoning that linked theory and evidence was completely convincing

IN-DEPTH INVESTIGATION: THEORIES OF COMBUSTION

READING: Lavoisier's Legacy

Oxygen: The Gas That Changed Everything describes the debate over what caused combustion. The theory of phlogiston proposed by alchemists stated that materials burned because they contained phlogiston, a transformative substance that made substances combustible. Therefore, every combustible substance was composed of phlogiston (which was liberated or released during combustion) and a residue.

Antoine-Laurent Lavoisier proposed a competing theory, the theory of oxygen. This theory states that a part of air called oxygen is taken up and incorporated into materials that burned. Lavoisier's theory was based on experimental evidence, including the evidence that the weight of the material present after combustion was greater than the weight of the starting material.

Lavoisier's ideas and approach to scientific work laid the groundwork for the development of the first modern atomic theory. In 1803, John Dalton, a British teacher and scientist, used experimental evidence to develop the first modern theory of the atom. Dalton proposed that all matter was composed of very small particles called atoms. Dalton's theory included four important ideas:

- The movement of atoms differs in each state—gas, liquid, and solid.
- The atoms of each element are the same in term of characteristics and weight, and these differ from atoms of other elements.
- Atoms of one element can combine with atoms of another element, resulting in different compounds.
- Atoms are indivisible and unchanging. Therefore, atoms do not change even when combined with other atoms, and the combination of atoms occurs in small, whole-number ratios such as 1:1 or 1:2.

Building on Dalton's theory, Italian physics professor Amadeo Avogadro clarified the nature of particles found in gases. He developed the idea of a molecule, which is a small particle made of atoms bound together. In 1811, Avogadro proposed that equal volumes of different gases at the same temperature contain equal numbers of molecules. About fifty years later Italian scientist Stanislao Cannizzaro used this idea to develop atomic weights for elements.

In 1865, Austrian high school teacher Johann Josef Loschmidt developed a method for estimating for the number of molecules in a given volume of air. This method led to the concept of the mole. The mole is a dimensionless unit equal to the number 6.022×10^{23}. This very large number is used to measure very small particles such as atoms and groups of atoms.

The mass of a mole of atoms has the same numerical value as the mass of that atom in atomic mass units (amu). For example, a carbon atom has a mass of 12.0 amu and, therefore, the mass of a mole of carbon atoms is 12.0 grams.

Similarly, the mass of a mole of identical groups of atoms in grams has the same numerical value as the mass of a single group of atoms in atomic mass units.

ACTIVITY: Analyzing a Combustion Reaction

The mole provides a way to determine the ratios of atoms in reactant products, such as those formed during combustion. In this activity, you will work with a group to predict changes in mass and then analyze experimental data for the combustion of magnesium, a very reactive metal, in order to determine the chemical formula of the product.

Prediction

Briefly describe the theories of phlogiston and oxygen. For each theory, explain if the mass of the product of the combustion of magnesium will be less or more than the mass of the magnesium metal. Note: Assume that phlogiston is a substance that has mass.

Experimental Data

An investigator finds the mass of a small container called a crucible and its cover. The investigator adds a small quantity of magnesium to the crucible and finds the mass of the crucible, its cover, and the magnesium. The investigator then heats the magnesium in air until combustion is complete. In the final step, the investigator finds the mass of the crucible, its cover, and the product of combustion.
The investigator recorded the following masses:

- Mass of crucible and its cover: 19.65 g
- Mass of crucible, its cover, and magnesium: 21.87 g
- Mass of crucible, its cover, and product of combustion: 23.38 g

Analysis

Working with your group, complete the following questions and be prepared to share your answers with the whole class.

1. From the experimental data, what is the mass of magnesium?
2. From the experimental data, what is the mass of the product of combustion?
3. Which combustion theory does the data support: phlogiston or the incorporation of oxygen? Explain.
4. Magnesium reacts with what gas during combustion?
5. From the experimental data, what is the mass of oxygen incorporated into the product of combustion?
6. What is the number of moles of magnesium (Mg) in the product of combustion? (Note: The mass of one mole of magnesium is 24 grams.)
7. What is the number of moles of oxygen (O) in the product of combustion? (Note: The mass of one mole of oxygen is 18 grams.)
8. What is the ratio of magnesium and oxygen atoms in the product of combustion? Explain your reasoning.

9. What is the chemical formula for the product of combustion of magnesium?
10. This experiment was repeated several times. In each case the same ratio of magnesium and oxygen was found. How does this result support Dalton’s theory of atoms?

WEB RESOURCES

Why many historians no longer see alchemy as an occult practice
http://www.usnews.com/science/articles/2011/02/24/alchemy-renaissance?s_cid=rss:alchemy-renaissance
Historical views often change with new information or new insights into the past. This site contains a short article that explains why historians of science have changed their evaluation of the role of alchemy. Alchemy was once viewed as a tradition that was detrimental to the development of modern chemistry. Now, alchemy is seen as the precursor to modern chemistry.

"The Chemical History of a Candle"
http://legacy.fordham.edu/halsall/mod/1860Faraday-candle.asp
Michael Faraday's life is an inspirational story in science. Born in the late 1700s, he began his working life as bookbinder, but later became one of the world's most renowned scientists and made numerous important discoveries. He admired Joseph Priestley for his work and originality of mind. Faraday believed in making knowledge accessible to all, and he started a tradition of giving lectures to young people at the Royal Institution in London, which were called the Christmas Lectures. These lectures still continue today. One of Faraday's most popular series was the six lectures that compose "The Chemical History of a Candle." This site reproduces the text of these six lectures and includes notes that help clarify points in the text. The lectures, given about a half century after Priestley's death, show how the understanding of chemistry had improved due to the work of Black, Priestley, and Lavoisier.

Earth's Atmosphere: Composition and Structure
http://www.visionlearning.com/en/library/Earth-Science/6/The-Composition-of-Earths-Atmosphere/107
This site is an online module on the atmosphere that includes readings, questions, quizzes, and related links.

Short Biographies of Joseph Priestley and Antoine-Laurent Lavoisier
http://www.chemheritage.org/discover/online-resources/chemistry-in-history/themes/early-chemistry-and-gases/priestley.aspx
http://www.chemheritage.org/discover/online-resources/chemistry-in-history/themes/early-chemistry-and-gases/lavoisier.aspx
The Chemical Heritage Foundation site contains information on the theme "Early Chemistry and Gases," which includes short biographies of Joseph Priestley and Antoine-Laurent Lavoisier found at the two links listed above.

An International Historic Chemical Landmark: The Chemical Revolution
https://www.acs.org/content/dam/acsorg/education/whatischemistry/landmarks/lavoisier/antoine-laurent-lavoisier-commemorative-booklet.pdf

This site reproduces the booklet that commemorates the designation of the chemical revolution as an International Historic Chemical Landmark. This booklet describes the work of Antoine-Laurent Lavoisier and his opposition to the theory of phlogiston. The booklet also describes how Lavoisier's colleague, Pierre-Samuel du Pont, brought his ideas to the United States. The American Chemical Society and the Société Française de Chimie jointly conferred the International Historic Chemical Landmark designation in 1999.

How Café Culture Helped Make Good Ideas Happen

http://www.npr.org/templates/story/story.php?storyId=130595037

This site explores the role of café culture. Joseph Black belonged to The Oyster Club in Edinburgh. Joseph Priestley belonged to the Club of Honest Whigs and the Lunar Society. Antoine and Marie Anne Lavoisier hosted parties at which scientists discussed ideas and problems related to chemistry. These clubs and gatherings are examples of café culture, a phenomenon that contributed to dramatic changes in ideas in all spheres of life in a time called the Enlightenment. The Enlightenment occurred in Europe and America from the mid-seventeenth century through the eighteenth century and is the basis for most of the beliefs of the modern western world.