2. Humphry Davy: Chemistry's First Showman

The previous section of the film ends with the idea that Antoine Lavoisier's identification of oxygen and his list of "simple substances" posed a new question for chemists: What *are* the elements?

CHAPTER 1: Precocious Chemist

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 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

- 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

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.

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.

Host scene in studio. He pulls down a world map showing the far-flung locations of the discoveries. The names of newfound elements appear on the screen: zirconium, uranium, titanium, yttrium, chromium, beryllium, vanadium, niobium, tantalum, palladium, cerium, osmium, iridium, tellurium, rhodium.

CONCEPT IN BRIEF: element

HOST

All over the world, chemists and amateur collectors responded to Lavoisier's challenge, rapidly identifying 15 new elements. From Sweden to Mexico, Connecticut to Siberia, the discoveries kept coming – sometimes as many as four in a single year. And few things could bring a chemist more glory than identifying a new element.

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

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

Davy talks with Coleridge, Southey and Cottle. As he holds forth about chemistry, they listen in amazement.

HUMPHRY DAVY

Well, certainly, Lavoisier was one of the great, great masters of all time. In fact, …

NARR: One of those who would soon be caught up in the hunt was a precocious chemist from the farthest reaches of England.

HUMPHRY DAVY

… pathetic ideas of phlogiston, huh?

POET ROBERT SOUTHEY, partly in VO

I've just met a remarkable young man whose talents I can only marvel at. He's not even 21 and has been studying chemistry for no more than 18 months, but he's advanced with such strides as to overtake everybody. His name is Davy … the young chemist … the young everything.

Notes from the Field:

Even though he lived so long ago, the fact that Davy was only 21 years old made my students view him like a peer.

Archival image of young Humphry Davy

NARR: Humphry Davy was the son of a simple wood-carver …

Map showing Penzance's remote location at England's southwestern tip

NARR: … from the remote seaside village of Penzance, about a week from London by stagecoach.

HISTORIAN DAVID KNIGHT, starting in VO

Penzance is right down in the far southwest corner of England, and in some sense it was the Wild West, right out beyond the influence of London and its institutions.

Historic Cornwall images, including apothecary interior

NARR: When his father died young, Humphry left school at 16 and took a job as an apothecary's apprentice to support the family.

17-year-old Davy reads a book by candlelight.

NARR: But he never lost his love of learning. He simply resolved to teach himself.

Now a CU reveals the book he is reading: Lavoisier's Traite Elementaire de Chimie

AUTHOR RICHARD HOLMES, partly in VO

The same year that Davy's father dies, Lavoisier publishes his *Elementary Treatise on Chemistry*. And young Davy reads this in the original French. He starts keeping notebooks from this very date. And there's a kind of intellectual explosion.

HUMPHRY DAVY, partly in VO

Chemistry arose from the delusions of alchemy, only to be bound by the chains of phlogiston. But through the discoveries of Black, Priestley and Lavoisier, it has now been liberated!

Davy continues reading.

HISTORIAN DAVID KNIGHT VO

Davy started doing experiments right away, and one of the things he did was to attack Lavoisier's theory of heat.

Notes from the Field:
I like to point out to my students that not every scientist in history came from a privileged upbringing. It's important for them to see that "normal" people can do science.

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

HISTORIAN RICHARD HOLMES, partly in VO

Lavoisier said it was a material substance called calorique. And Davy didn't believe this.

CONCEPT IN BRIEF: matter

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Davy rubs two pieces of ice together and observes that the friction causes them to melt.

HISTORIAN DAVID KNIGHT, partly in VO

Davy thought he could take on the great man. He thought heat was motion of particles. And he thought he could prove this if he could rub two pieces of ice together – so no heat would be coming in from outside – and the sheer friction would melt the blocks of ice. And that's what happened. To him and his contemporaries, the experiment was a convincing one.

Chapter 2: Davy in Bristol

Alignment with the NRC's National Science Education Standards

F: 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.
- Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve assessment of alternatives, risks, costs, and benefits and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them.

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 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

- 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.

Alignment with the Next Generation Science Standards

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.

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.

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.
   - Make and defend a claim based on evidence about the natural world that reflects scientific knowledge.

8. Obtaining, Evaluating, and Communicating Information
   - Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.

Image of his first work: An Essay on Heat, Light and the Combinations of Light

NARR: Davy's findings, written up in his first published work, showed enough promise …

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

Map shows path from Cornwall to Bristol, about half the distance to London.

NARR: … to land him a post closer to Britain's center of action, in Bristol …

Photo of the Pneumatic Institution

NARR: ... at the Pneumatic Institution.

HISTORIAN RICHARD HOLMES, partly in VO

So he leaves remote Penzance to become the assistant and then the director of this new institute. He's only 19, for heaven's sake!

Dr. Robert Kinglake detaches a green silk bag from a forge, where it has been filling with gas, and hands it to Davy.

NARR: The institution had been founded in the hope that some of the gases discovered by Priestley and others would prove useful in treating diseases.

STOP AND THINK 1: Why do you think that doctors in Davy's time were interested in the medical effectiveness of new chemical discoveries?

Possible Student Answers: Students' answers to this question will vary. Students may suggest that because doctors did not have much information about how the body and mind worked, they were open to using trial and error to find medicines.

Davy inhales the gas and stops to consider the sensation. He flexes his fingers.

NARR: Davy's job was to make the gases – and then test them.

CONCEPT IN BRIEF: science in personal and community health

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

HUMPHRY DAVY, partly in VO
I took just three breaths of the gas. The first produced a feeling of numbness.

NARR: One of the gases he tested was mostly carbon monoxide – the poisonous gas now found in auto exhaust.

Re-enactment continues. Davy inhales the gas a second time.

AUTHOR RICHARD HOLMES, partly in VO
He doesn't know exactly what it is, but he makes it. And he tests everything on himself. It's amazingly reckless, but it's also very brave.

Notes from the Field:
I always like to make comparisons between historical experiments and the safety measures we currently use. The kids are so surprised to see something like a scientist inhaling gases!

The mouthpiece drops from his mouth as Davy slumps over.

PUBLISHER JOSEPH COTTLE, partly in VO
He acted as if in sacrificing one life, he had two or three others in reserve. Some days, I half despaired of seeing him alive the next morning.

Kinglake rouses Davy from unconsciousness and gets him a glass of water. Davy takes his own pulse.

CONCEPT IN BRIEF: risks associated with scientific discovery

AUTHOR RICHARD HOLMES, partly in VO
And then he takes his pulse, and he says: "*I do not think I shall die.*" And he is ill for 48 hours, but he survives. On a number of occasions, he does nearly kill himself.

As Kinglake looks on, concerned, Davy begins to recover.

HISTORIAN DAVID KNIGHT, partly in VO

When you've got a career to make and you're coming from a low point down the social scale, and you've got a long way to go, why not take a few risks, get your way up to the top quicker?

STOP AND THINK 2: Do you think that Davy was brave or reckless or both by breathing in unknown gases?

Possible Student Answers: Students' might take a variety of positions. You might wish to discuss issues of safety in relation to the ingestion of dangerous or unknown substances.

Pan down page in Bristol notebook to reveal: "Davy and Newton"

NARR: The top Davy had in mind was the very pinnacle of science. On one page of his Bristol notebooks, he wrote his own name next to that of the most famous British scientist of all time.

Double portrait of Newton and Davy

AUTHOR RICHARD HOLMES, partly in VO

Newton … and Davy. So he has this sense that he and Newton can go at science together. It's not arrogance exactly. It's this tremendous drive, and he passionately believes that he … will be … a sort of Newton in chemistry.

Davy speaks to his literary friends.

HUMPHRY DAVY

I don't hesitate at all. The great master made a few mistakes.

AUTHOR RICHARD HOLMES VO

All his life, that drive is there: Newton and Davy.

Continuation of first scene with Davy discussing chemistry with the men of letters. Pan of the three men as they're identified in narration.

NARR: In Bristol, Davy sought out a group of literary men whose work would define the Romantic Age, including publisher Joseph Cottle and poets Robert Southey and Samuel Taylor Coleridge.

CONCEPT IN BRIEF: influence of society and culture on science

Discussion continues.

HUMPHRY DAVY
… the assumption that heat is a simple substance.

SAMUEL TAYLOR COLERIDGE
Is that what he called caloric?

HUMPHRY DAVY
Precisely.

AUTHOR RICHARD HOLMES, partly in VO
In looking at that group in Bristol, one of the things that I think is wonderful: there was no gap between the writers and the poets and the scientists.

Discussion continues.

HUMPHRY DAVY
We can discover that the ice melts by friction alone.

ROBERT SOUTHEY
Davy, could not the melting have been caused by the temperature of the room?

HUMPHRY DAVY
That's a very good question, indeed – one to which I have a ready answer. The air …

AUTHOR RICHARD HOLMES, partly in VO
Every evening, they're going out, writing letters to each other, going on walks together. And they are young men with a future. It's an extraordinary group.

NARR: In Davy these Romantic poets found a kindred spirit …

HUMPHRY DAVY
When we remove the ice from the point of friction, it refreezes …

NARR: … a scientist who shared their sense of wonder at Nature and yearned to reveal her mysterious ways.

Notes from the Field:
My students were curious why these people with such varying interests were drawn to each other and what they had in common.

EXAMPLE OF SCIENCE PRACTICE: engaging in argument from evidence

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

CONCEPT IN BRIEF: heat

CONCEPT IN BRIEF: matter

HUMPHRY DAVY
Heat must, in fact, be the motion of particles.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

POET SAMUEL TAYLOR COLERIDGE
There's an energy – an elasticity – in his mind that allows him to seize on and analyze all subjects. Living thoughts spring up like turf under his feet.

STOP AND THINK 3: What evidence did Davy use to refute Lavoisier's assertion that heat is a substance?

Possible Student Answers: Davy carried out an experiment to show that motion results in heat.

Chapter 3: Laughing Gas

Alignment with the NRC's National Science Education Standards

B: Physical Science

F: Science and Technology in Local, National, and Global Challenges

- Progress in science and technology can be affected by social issues and challenges.

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 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

- 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.

Kinglake generates a gas from a tabletop apparatus. Davy sits in the "subject chair" and inhales this gas from a blue silk bag. He feels a "thrilling" sensation.

NARR: Early in his research, Davy produced a gas one medical authority had warned was the cause of terrible diseases. He tried it anyway.

Notes from the Field:

I made sure to point out the negative health effects of using laughing gas like Davy did, and we discussed the risks of taking a substance without being informed of its effects.

HUMPHRY DAVY, partly in VO

This evening I breathed nitrous oxide and experienced a thrilling all over me – more pleasurable than anything I have ever experienced.

Davy puts the bag down, stamps his feet, laughs uncontrollably, dances around the room.

HUMPHRY DAVY VO

The objects around me became dazzling and my hearing more acute. Sometimes I responded by stamping my feet, other times by dancing around the room and laughing uncontrollably.

Southey tries the gas, considers the sensation.

NARR: As word of his discovery spread, many others – from steam engine pioneer James Watt to the king's own doctor – clamored to try Davy's "laughing gas."

HISTORIAN DAVID KNIGHT, partly in VO

Coleridge and Southey both took doses of the gas. It was very much in keeping with this Romantic time period.

Southey responds to the gas, laughing at Davy and Kinglake.

POET ROBERT SOUTHEY, partly in VO

He's invented a whole new pleasure. It makes you laugh and tingle in every toe and finger-tip.

HISTORIAN DAVID KNIGHT VO

There was a certain amount of recklessness, experimenting with drugs. Why not expand your consciousness?

POET ROBERT SOUTHEY, partly in VO

It makes you strong and happy! So gloriously happy! Oh, excellent airbag. I'm going for more this evening.

Coleridge breathes the gas. Davy watches attentively. Coleridge laughs. Davy takes away the gas bag – you've had enough.

NARR: Davy asked each of his subjects to record their impressions.

POET SAMUEL TAYLOR COLERIDGE, partly in VO
The first time I tried nitrous oxide, I felt a highly pleasurable sensation of warmth over my whole body. It was like the feeling I once experienced entering a warm room after returning from a walk in the snow. I felt no desire to move – only to laugh at those who were looking at me.

EVERYDAY APPLICATION 1: Because nitrous oxide causes a loss of feeling, sensation, or pain, it is used as an anesthesia for dental surgery. It is also used as an inert food additive that prevents bacterial growth in packaged foods a foaming agent for food sprays, whipped cream, and soaps; an additive to gasoline and rocket fuel that increases combustion; and a gas that trains underwater divers to recognize the symptoms of nitrogen narcosis.

STOP AND THINK 3: One risk of Davy's experimentation with laughing gas was addiction. His inhalation of toxic gases in general is also considered the cumulative cause of his death at age 50. However, his risky experimentation paved the way for several discoveries, including the discovery of an anesthesia that suppresses pain during surgery. Was this kind of risk acceptable? Why or why not?

Possible Student Answers: Students' will take a variety of positions because the assessment of risk is both individual and societal.

Image of Davy writing. Image of Davy's book: Researches, Chemical and Philosophical, Chiefly Concerning Nitrous Oxide and its Respiration

NARR: Davy wrote up their accounts in his first true scientific book. But just as he was finishing the book, Davy's attention was diverted by a discovery that would shake the very foundations of science.

Chapter 4: The First Battery

Alignment with the NRC's National Science Education Standards

B: Physical Science

Chemical reactions:

- Chemical reactions may release or consume energy.

Motions and Forces:

- The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel.

G: History and Nature of Science

Nature of Scientific Knowledge

- 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.

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.

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.

Painting of Volta showing the pile to Napoleon

NARR: In 1800, an Italian named Alessandro Volta announced that he had created a new source of electricity.

Image of Franklin harnessing lighting. CU of spark from electrostatic generator, from the Priestley footage. Priestley's son watches, amused.

NARR: Up to then, the only sources of electricity had been lightning, which was very difficult to tap, and electrostatic devices like the ones Priestley had used.

JOSEPH PRIESTLEY

"How are you doing that?"

HISTORIAN DAVID KNIGHT, partly in VO

You could get quite spectacular effects in the way of flashes and bangs. But you couldn't get sustained power. What Volta did was to establish that electricity was something that you could make a steady supply of – what we call an electric current.

Host scene, with voltaic pile and archival image of Volta

HOST

Volta's device was incredibly simple – a sandwich of alternating copper and zinc disks, separated by pieces of cardboard that had been soaked in salt water. But this "voltaic pile" – the first battery – electrified the world of science.

EVERYDAY APPLICATION 2: Batteries are a widely used source of electricity, with yearly worldwide sales of batteries exceeding 50 billion dollars. The advantages of batteries are their portability and reliability, which result in their use in mobile and backup applications such as cell phones and hospital generators. There are two main types of batteries: primary batteries that are single use and secondary batteries that can be recharged for multiple uses. The drawbacks of batteries are their high cost and their use of toxic substances. Always recycle batteries to help prevent ground and water contamination by toxic substances.

HISTORIAN ALAN ROCKE

With the battery, you could now perform a variety of experiments that had never been possible before. And these experiments were done *immediately*.

CONCEPT IN BRIEF: battery

Host motions to the two overturned test tubes in which hydrogen and oxygen have collected.

HOST

Just weeks after learning of Volta's discovery, two British scientists used a crude battery like this one to split water into its two elements: hydrogen and oxygen.

HISTORIAN DAVID KNIGHT

The electric current was somehow *breaking up* the water into its components.

STOP AND THINK 4: Electricity is a source of energy. Why might energy be needed to split water into oxygen and hydrogen gases?

Possible Student Answers: Students might explain that energy is needed because water has lower energy than oxygen and hydrogen gases. Students might label the electrolysis reaction as an endothermic reaction.

Over each electrode is a test tube that gradually fills with gas. As the host mentions hydrogen, he removes and lights one tube, which emits a short pop as the hydrogen explodes. When he removes the oxygen tube and inserts a lighted splint; we see the same brightening we saw in Priestley's lab.

CONCEPT IN BRIEF: importance of scientific tools

HOST

Even more surprising, the hydrogen collected at the negative electrode over here ... and the oxygen collected at the positive electrode, over here. Why would these two elements show a preference for opposite electrical charges?

STOP AND THINK 5: When the battery was first used to split water, scientists, including Davy, wondered why the hydrogen and oxygen gases collected at the different electrodes. What is your explanation for this phenomenon?

Possible Student Answers: Students might explain that since the hydrogen atoms in the water molecule are more positive, they are attracted to the negative electrode. Students might also explain that hydrogen ions can be pulled away from the water molecule and then combine with electrons at the negative electrode to form hydrogen gas.

Davy begins his first experiment on electricity.

CONCEPT IN DETAIL: battery

NARR: Intrigued, Davy set aside his research on gases, built a voltaic pile and began doing his own experiments on electricity.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

HISTORIAN DAVID KNIGHT VO

And it became Davy's big pursuit in life. What could this electric current do?

HUMPHRY DAVY, partly in VO

Volta has given us a key to some of the most mysterious recesses of nature. Till this discovery, our tools were limited. Now the possibilities for chemistry seem boundless. It's like an undiscovered country – a land of promise.

Chapter 5: Chemistry's Showman

Alignment with the NRC's National Science Education Standards

G: History and Nature of Science

Science as a Human Endeavor

- 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.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

8. Obtaining, Evaluating, and Communicating Information

- Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.

Davy peers at the bubbles rising in his test vessel.

NARR: Davy had just begun to explore that land when opportunity knocked.

Reprise shot of book

NARR: His book on nitrous oxide had caught the attention of the founders …

Archival image of the Royal Institution on Albemarle Street, ca 1800

NARR: … of the new Royal Institution in London, who were looking for a director for their chemistry laboratory.

Table of contents showing technical details

AUTHOR RICHARD HOLMES, partly in VO

And that book had such impact that it was read in London, here at the Royal Institution. It's very, very precise. It's measured. It's quantitative science. And they thought, "This is the man we must get."

Painting of Davy. Then on a map of England, the path from Bristol to London is traced out.

NARR: Still only 22, Davy set out on his next great adventure, leaving Bristol in 1801 for the city he called …

Archival image of London ca 1800

NARR: … "the great hot-bed of human power."

Archival image of young Davy

HISTORIAN DAVID KNIGHT, partly in VO

When Davy arrived, his patrons seem to have been a bit taken aback to find this still rather raw, country youth. But his natural eloquence must have come through and eventually charmed them.

Painting of the RI library

NARR: One of the missions of the institution was to offer public lectures meant to stimulate an interest in science among the London elite.

View of the Royal Institution in 1800

NARR: For this purpose a theater had been installed in the institution's building on Albemarle Street.

James Gillray cartoon showing laughing gas experiments at the RI. Davy, in the background. is highlighted as his position is identified.

NARR: Davy started out as assistant lecturer – seen here helping his boss give a dose of laughing gas to one of the patrons. But with audiences shrinking and the institution's fortunes flagging, Davy was quickly promoted to the top job.

Davy rehearses his lecture as two of his assistants listen.

HUMPHRY DAVY
Nothing is so fatal to the progress of the human mind …

NARR: Determined to make the most of this opportunity, he set out to make each lecture seem spontaneous.

AUTHOR RICHARD HOLMES, partly in VO
But to do spontaneous what he did was prepare, prepare.

HUMPHRY DAVY
… as to suppose that there are no mysteries left in nature.

STOP AND THINK 6: Davy says that human progress will cease if people think that they have found everything there is to know. Do you agree with this idea? Why or why not?

Possible Student Answers: Students might agree because people can only gain new understandings and develop new theories by finding out new information and new data. Students might also agree because this statement acknowledges the complexity of the natural world.

AUTHOR RICHARD HOLMES, partly in VO
He would read through, in front of his assistants, drafts of the lecture to see if it worked.

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

HUMPHRY DAVY
Who would not want to learn the most profound secrets of Nature – to ascertain her hidden operations?

Exterior of the RI, sound of Davy's voice coming from inside, ramping up under Holmes' bite. Huzzahs from the audience

AUTHOR RICHARD HOLMES, partly in VO
The moment Davy began to lecture, the audiences packed in.

HUMPHRY DAVY VO
Science has done much for man, but it is capable of doing still more.

HISTORIAN DAVID KNIGHT
He had people absolutely lapping up what he was pouring out.

Surrey Institute drawing of Davy competitor

NARR: There were other chemists giving public talks elsewhere in London ... but none held a candle to Davy.

Davy rehearses his lecture, his eyes flashing. Then he practices a demonstration with his assistants.

DAVID KNIGHT, partly in VO
He must have directed his bright eyes around his audience so that they felt really drawn in and mesmerized. And he would do dazzling experiments that he carefully rehearsed with his assistants the night before, so they always worked.

STOP AND THINK 7: Most of the people who came to Davy's lectures were not scientists. Davy carefully prepared his lectures, and as a result, his demonstrations and explanations of scientific processes and discoveries were clear and understandable. Why is it important for scientists to clearly communicate their work to all people?

Possible Student Answers: Students' answers might include the idea that since decisions about how to use science are carried out by society as a whole, it is important that all people understand basic concepts and principles of science and technology. Students' answers might also include the idea that it is important for all people to understand that scientific explanations are based on experimental and observational evidence about nature, are logical, and are open to critique and revisions as new evidence becomes available.

Image of RI exterior, sounds of delight coming from inside

RICHARD HOLMES VO

And people gasp, and they cheer and they clap at the end of a demonstration, it's so brilliantly done.

CONCEPT IN BRIEF: influence of society and culture on science

Drawing showing a carriage-choked Albemarle Street

AUTHOR RICHARD HOLMES, partly in VO

And these lectures became *hugely* popular. There were terrible traffic jams outside the Royal Institution. Albemarle Street became the first one-way street in London, because there were so many carriages bringing people to listen to his lectures.

Image of attractive young Davy

HISTORIAN ALAN ROCKE, partly in VO

He was young. He was handsome. He was eloquent. And there were a number of young ladies in the audience.

Cartoon close-ups showing ladies in the audience

AUTHOR RICHARD HOLMES, partly in VO

They are all in the front rows making notes, but hanging on Davy's every word. Among the lecture notes in the Royal Institution archive are these little *billets-doux,* little love letters, often signed with a pseudonym, and poems to him!

Archival image of Davy, CU of eyes

NARR: One of his female admirers invited him to dinner, noting: "Those eyes are too fine to be forever gazing over crucibles."

HUMPHRY DAVY

I have audiences of four or five hundred people, many of high rank, and I suspect that some of them may become permanently interested in chemistry. This science is becoming the fashion of the day.

Chapter 6: New Elements

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms:

- Matter is made of minute particles called "atoms," and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge.

Motions and Forces:

- The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel.

G: History and Nature of Science

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

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.

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.

Disciplinary Core Ideas

- The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms.
- Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.

Painting of Davy

NARR: Davy's success as a lecturer and entertainer brought him wealth, prizes, and acclaim. But he was growing impatient. Giving popular lectures was no way to become the Newton of chemistry.

CONCEPT IN DETAIL: battery

Image of Davy

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

HISTORIAN DAVID KNIGHT, partly in VO

By 1806 he had established enough of a reputation, and he knew that his work was supporting the Royal Institution. He could say, "Right. I've been doing your work for the last five or six years. Now I'm going to do my own work."

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

Image of the Royal Society building

NARR: An invitation from an organization once headed by Newton himself gave Davy the perfect chance to show what he could do.

Image of Royal Society room

AUTHOR RICHARD HOLMES, partly in VO

He was asked to lecture not to the Royal Institution but to the Royal Society, the top scientific group in the world. He needed to produce some dramatically original science.

Reprise image of Davy studying his electrical cell in Bristol

NARR: With this goal in mind, Davy dived into the subject he'd been itching to return to ever since Bristol …

Lightning bolt splits the sky in Franklin painting.

NARR: … electricity.

HUMPHRY DAVY

Up to now, we have studied electricity only its most powerful form: lightning. But its slow and silent operations on the earth's surface may prove more important.

Davy watches the bubbles.

NARR: From his early experiments, Davy had learned that an electric current could pry apart the hydrogen and oxygen atoms that made up water.

AUTHOR RICHARD HOLMES

You can use a battery to *un-bond* things and find out what the different elements are.

Davy again looks at Bristol battery.

NARR: That gave Davy an idea: Could he use a bigger battery to tackle substances that were harder to break down?

HISTORIAN ALAN ROCKE, partly in VO

This is something you can do with this new source of electricity. If a small battery gives you a small effect, build a larger one and you get a larger effect.

Page from Davy's notebook, CU of word "potash."

NARR: As the target for his experiment, Davy chose caustic potash …

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Images of ash collection pot, then ashes inside the pot.

NARR: … a substance derived from wood ashes collected in a pot. Chemists had long suspected it contained an undiscovered element, but no one had been able to break it down into simpler stuff.

AUTHOR RICHARD HOLMES

He believed that if you could apply a charge to it in some way, you would discover something about its inner nature.

Davy and his assistant tend his big bank of batteries at the RI.

HISTORIAN ALAN ROCKE, partly in VO

So Davy constructed a really big battery, because he wanted to see whether potash could be decomposed into its elements.

HISTORIAN FRANK JAMES, partly in VO

Davy was thus able to use the resources of the Royal Institution to undertake scientific research, which had never been the intention of the founders of the RI.

Assisted by his cousin Edmund, Davy carries out his experiments with potash, starting with a watery mix.

NARR: But by the time he began the work, his Royal Society lecture was only a month away.

HUMPHRY DAVY (to assistant)

Shall we?

CONCEPT IN BRIEF: Electricity

AUTHOR RICHARD HOLMES VO

He committed himself rather recklessly, because he didn’t really have much time.

NARR: Would this new battery be strong enough to reveal what potash was made of?

AUTHOR RICHARD HOLMES VO

Working at top speed, he tries various ways of applying the charge.

Davy checks to see if his experiment is working. His expression tells us it’s not.

NARR: Davy first tried putting a current through a mixture of potash and water. All that did was split the water into hydrogen and oxygen ...

HUMPHRY DAVY (to assistant)

Do you see anything?

NARR:... leaving the potash unaffected.

Now he applies the battery to dry potash, again without success.

HISTORIAN DAVID KNIGHT, partly in VO

And then he tried with dried potash, and again, nothing happened.

Now he dampens the potash before connecting the battery. Success! CUs of potassium reacting violently.

Notes from the Field:

This is a great example of how science is carried out. Davy just kept trying and trying. He had an idea he was onto something but had to keep tweaking his experiment until he got results.

NARR: Finally, he moistened the dry potash just a bit before applying the electricity.

HUMPHRY DAVY, partly in VO

Dry potash won't conduct electricity, but when I added a little water and applied a strong electrical current … I soon observed a vivid action. There was a violent effervescence … and small globules.

AUTHOR RICHARD HOLMES

It sweats forth these glowing, shining globules.

CU of the silvery globules

HUMPHRY DAVY, partly in VO

They have a metallic luster very much like mercury, and some of them exploded and burnt with a bright flame. I realized these globules were the substance I had been searching for.

Edmund Davy watches as Humphry performs the experiment.

AUTHOR RICHARD HOLMES, PARTLY IN VO

And this is a new element, in fact. It's potassium, one of the crucial elements for life. And he's discovered it. There's a wonderful description made by his assistant, who was actually Edmund Davy, a young cousin. He said, "The Professor became a boy again."

EVERYDAY APPLICATION 3: Potassium is a very reactive element and, therefore, only potassium *compounds* are found in nature, never the elemental metal. Potassium compounds are used in fertilizers, soaps, matches, explosives, and fireworks; for the production of oxygen in respiratory equipment; and in the manufacture of glass. A potassium-sodium alloy (NaK) is used to transfer heat in some types of nuclear reactors.

Davy laughs and claps Edmund on the chest in celebration.

EDMUND DAVY, partly in VO

When he saw those globules of potassium burst through the crust of potash and catch fire, he couldn't contain his joy. It was some time before he could compose himself and continue with the experiment.

Davy gradually calms down. CUs of the elements he has created.

AUTHOR RICHARD HOLMES, partly in VO
You get the sense of this huge excitement, doing things under pressure, not quite knowing what will happen, whether the damn thing will explode. And then suddenly the unknown reveals itself.

HISTORIAN DAVID KNIGHT, partly in VO
The atoms of potassium and oxygen, so firmly glued together, could be separated by an electric current in the same way as those oxygen and hydrogen atoms in water.

Page of Davy's notebook. Zoom to "decomp of soda."

NARR: The very next day, Davy used the same method to pull apart caustic soda, or lye, to reveal another new element: *sodium.*

EVERYDAY APPLICATION 4: Like potassium, sodium is a very reactive element and, therefore, only sodium compounds are found in nature, never the elemental metal. Almost all sodium compounds dissolve in water, so most sodium compounds on land are found in deserts. Deserts contain large quantities of sodium chloride (table salt) and this compound is mined and used in the food industry for flavoring and preserving foods. Sodium chloride is also used for the production of other sodium compounds that are used in baking soda, baking powder, drain cleaners, soaps, water purification, aspirin and other drugs, and in the manufacture of glass. Sodium metal is chemically extracted and used as a catalyst. Sodium metal is also used as a gas inside lamps, particularly street lamps. Sodium lamps give off a yellow light.

EVERYDAY APPLICATION 5: Davy used a battery to isolate sodium for the first time. Today, sodium metal is used as a reactant in certain batteries. Sodium-based batteries supply a large amount of energy for their size, can last longer than 15 years when regularly recharged, can be used in extreme temperatures, have no emissions, and are made of materials that are easily recycled. For these reasons, sodium-based batteries are used in electric vehicles and in wind-power and solar-power devices. With further development, rechargeable sodium batteries might replace lithium batteries for consumer electronics use.

While Edmund and Humphry watch, John Davy cuts potassium into pieces and tosses them into water, where they explode in lavender flames and billows of smoke. The three react with delight.

NARR: These two new metals were so soft they could be cut with a knife – and so eager to recombine with oxygen that they gave Davy the perfect demonstration for his next lecture.

Exterior of Royal Institution, popping sounds (from earlier scene), followed by applause from within.

NARR: Davy had turned electricity into a powerful tool in the search for new elements.

Over wide shot of Davy working in the lab, the names of four more new elements appear on the screen: magnesium, calcium, strontium and barium.

NARR: The year after discovering potassium and sodium, he used his battery to isolate four more elements.

Over images of other pioneers in electrochemistry appear the names of five other elements they discovered with electricity: boron, iodine, lithium, silicon, aluminum.

CONCEPT IN DETAIL: importance of scientific tools

NARR: And chemists all over Europe seized on his technique, sending the number of elements even higher.

Shot of Davy's big battery.

HUMPHRY DAVY, partly in VO

Sometimes the progress of science is due less to our intellectual powers than to the tools at our disposal. Nothing promotes the advancement of knowledge so much as a new instrument.

STOP AND THINK 8: Davy was able to find new elements by using a method made possible by a new technology—the battery. How are technology and science intertwined?

Possible Student Answers: Students' answers might include the recognition that new technology like the battery extends what scientists can do and observe and leads to the development of new scientific knowledge. Students' answers might also include the recognition that new scientific knowledge, in turn, can lead to the development of new technology.

Chapter 7: Electric Glue

Alignment with the NRC's National Science Education Standards

B: Physical Science

Chemical reactions:

- Chemical reactions may release or consume energy.

Motions and Forces:

- The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel.

G: History and Nature of Science

Nature of Scientific Knowledge

- 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.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

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.

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 structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms.
- Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.

Davy and his assistant continue working in the lab.

NARR: Exciting as these discoveries were, in time it would become clear that Davy's greatest contribution was his insight into one of the biggest questions in chemistry.

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

CONCEPT IN BRIEF: matter

Return to Bristol electricity scene

HISTORIAN DAVID KNIGHT, partly in VO

Somehow the particles of matter have to be glued together to form molecules. And it was a complete mystery as to what this glue might be. What Davy has had, in effect, is a big idea.

CU of the voltaic pile, Davy in thought

NARR: If electricity could pry apart the atoms in water, potash and soda, might electricity be the force that stuck those atoms together in the first place?

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

HUMPHRY DAVY

Is electricity an essential property of matter?

Animation: Blobs representing hydrogen and oxygen are attracted to each other. One is positive, the other negative.

HISTORIAN DAVID KNIGHT VO

Perhaps electricity, with its plus and minus aspects, could be this kind of glue.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

EXAMPLE OF SCIENCE PRACTICE: developing and using models

HUMPHRY DAVY, PARTLY IN VO

In every case that we know of, substances that combine with each other have opposite electrical states. Now perhaps this is the reason they're attracted to each other – because opposites attract.

Davy experiments with electricity.

HISTORIAN DAVID KNIGHT, partly in VO

It looked as if electricity might play in chemistry the sort of role that gravity played in Newtonian physics.

Notes from the Field:

This is a critical concept for my students, and seeing how scientists made this discovery helps them understand the connection between chemistry and electricity.

Davy statue

AUTHOR RICHARD HOLMES, partly in VO

Remember, he thinks of himself as on a par in some way with Newton. He is going to be the Newton among chemists. And in a sense he does eventually achieve that.

CONCEPT IN DETAIL: matter

CONCEPT IN DETAIL: electricity

Footage of Priestley and his son doing the paper trick with the electrostatic generator

HISTORIAN DAVID KNIGHT VO

In the 18^{th} century, electricity was mostly parlor tricks, like making somebody's hair stand on end and attracting little bits of paper and so on.

Archival image of Davy

HISTORIAN DAVID KNIGHT, partly in VO

Davy showed that electricity is a fundamental aspect of matter. Electricity is what holds us together. It is the glue that links the particles of matter. And, therefore, instead of being rather a side thing, electricity is going to be one of the really central features of science.

Reprise shot of Davy behind host

HOST

It would take more than a century for other scientists to figure out electricity's role. But after Davy there was no doubt it would be one of the keys to solving the mystery of matter.

Fade to black

Fade up to establishing shot of Mendeleev – he gets an idea and reaches for a piece of paper.

VO

Next time on *The Mystery of Matter*…

Mendeleev finds a pattern among the elements.

HISTORIAN MICHAEL GORDIN VO
He figures out something extraordinary about the elements.

DMITRI MENDELEEV, partly in VO
The eye is immediately struck by a pattern – a regular change in the horizontal rows and the vertical columns.

Mendeleev's first Periodic Table is rotated 90 degrees and dissolves into the familiar Periodic Table of the Elements.

AUTHOR ERIC SCERRI VO
He had actually discovered an absolutely fundamental principle of nature.

Marie Curie repeats her measurements again and again.

EVE CURIE VO
My mother made her measurements over again – ten times, twenty times – until she was forced to accept the results.

The results keep coming out the same. Marie looks at Pierre: This is real.

MARIE CURIE, VO
I proposed a new term to define this property of matter: radioactivity.

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.

Production credits

ANNOUNCER: To learn more about the search for the elements and watch bonus videos on the featured scientists, visit pbs.org/mysteryofmatter. *The Mystery of Matter: Search for the Elements* is available on DVD. To order, visit shopPBS.org or call 1-800-PLAY-PBS.

Chapter 8: The Third Man

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

- 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.

Content Banner: ***More from*** **The Mystery of Matter**

Footage of Priestley with the two candles

NARR: Joseph Priestley was the first to publish his discovery of the remarkable gas we call oxygen.

Screen splits to make room for footage of Lavoisier at his scale.

NARR: Antoine Lavoisier was the first to understand its true significance.

Screen splits again and outline of mystery man appears alongside the others.

NARR: But there's a third man in the oxygen story.

The outline fills in with an image of Scheele.

NARR: a Swedish apothecary named Carl Wilhelm Scheele.

HISTORIAN SEYMOUR MAUSKOPF, beginning in VO
... who is also rather like Priestley, a wonderful experimentalist. In fact, he made the discovery before Priestley did, possibly as early as 1771.

Composite image of Scheele's book and his tardy mentor, Torbern Bergman

NARR: But when he discovered the gas he called "fire air," Scheele decided to publish his results in a book – and waited years for his mentor to write the preface.

CHEMIST ROALD HOFFMANN, partly in VO

The book doesn't get published till 1777, by which time all the chemists of Europe had already heard about Priestley's and Lavoisier's work.

Four elements are highlighted in the Periodic Table: chlorine, manganese, barium and molybdenum

NARR: While Scheele's discovery of oxygen had no impact on the course of science, he did go on to have a hand in the discovery of four more elements.

CHEMIST GREG PETSKO

… and got zero credit for this. First of all, he was a pharmacist and nobody paid any attention to him. Second, he was working in Sweden, and most of the scientific world paid zero attention to what was happening in Sweden. And third, he had the misfortune to die rather young as a result of his own experiments. He was constantly sniffing terrible chemical substances and was eventually found dead at his desk with so many toxic materials around him that to this day, nobody has any idea exactly what he died of.

ACTIVITY IDEAS

Research Batteries

Have student research batteries. Have students determine what voltage and size (D, C, A, AA, AAA) mean, and also have them describe several types of batteries and their uses.

Compare Different Batteries in Circuits

Have students measure voltage across one and two batteries using a multimeter. Have students see that voltages can add when batteries are connected in series in the correct orientation. Then have students build circuits using a bulb and one battery and a bulb and two batteries in series. Students will see that the circuit that is connected to the higher voltage results in a brighter light, or more energy. Have students explain the relationship between the energy of the light bulb and the energy released in the battery's chemical reaction. Have students speculate about what voltage measures. Then explain that voltage is a measure of energy per unit of charge moving through the wire, and this energy is the energy released in the battery's chemical reaction. Also, explain that the electrons moving through the wire are part of the chemical reaction and are moving from one substance at one end of the battery to the substance at the other end of the battery. You may want to also introduce the idea of reversible reactions in the context of recharging a battery.

Make Batteries

Have students make batteries and introduce redox reactions as reactions in which electrons are transferred. The battery reactions will show how the substances at each electrode react when electrons are transferred. Measure the voltage generated during the reaction.

Demonstrate Cathodic Protection

One of Davy's many discoveries was the use of cathodic protection, which is the prevention of corrosion of a metal by adding a more reactive metal that will corrode first. (This technique is used in water heaters, among many examples). Have students take two 6-penny iron nails and clean both with sandpaper. Then have them wrap one nail tightly with 10 cm of zinc wire and place both nails into a 10% sodium chloride solution. Student should observe the nails over a period of several days. Have students discuss their observations and relate the results to the use of galvanized nails, which are iron nails coated with zinc.

TEACHER NOTES

IN-DEPTH INVESTIGATION: ELECTROLYSIS

Context

During the historical period when *Humphry Davy: Chemistry's First Showman* takes place, citizen scientists and chemist all over the world were attempting to find fame by identifying new elements. Humphry Davy would use a new technology (the battery) and a new technique (electrolysis) to chemically separate compounds and identify new elements.

Overview

Students read about the distinction between elements and compounds and the use of electrolysis to chemically separate compounds into elements. Students view a demonstration of electrolysis and discuss their observations.

Next Generation Science Standards Alignment

Science and Engineering Practices

5. Using Mathematics and Computational Thinking
    - Use mathematical representations of phenomena to support claims and explanations.
6. Constructing Explanations and Designing Solutions
    - Apply scientific ideas to provide an explanation of phenomena.

Disciplinary Core Ideas

- The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms.

Crosscutting Concepts

- Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena.

Understanding Goals

Students should understand:

- There are two main kinds of substances: elements, which contain one kind of atom, and compounds, which contain two or more kinds of atoms.
- Whether a substance chemically decomposes can be used to distinguish between compounds and elements.
- Electrolysis is a process in which a chemical change, especially decomposition, is brought about by passing an electric current through a substance.

Student Materials

You will find on the following pages a reading and instructions for observing an electrolysis demonstration.

Electrolysis Demonstration Facilitation

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

Electrolysis Demonstration Rubric

Criteria	Not evident	Limited	Developing	Competent	Accomplished
Conclude if water and the gases produced are compounds or elements	No claims	Claims made, but explanation for one or more substances did not include evidence	Claims made and explanations included evidence, but for one or more substances the reasoning that linked claim and evidence was not convincing	Claims made and explanations included evidence, and for all three substances the reasoning that linked claim and evidence was somewhat convincing	Claims made and explanations included evidence, and for all three substances the reasoning that linked claim and evidence was completely convincing
Write the chemical formulas of water, oxygen, and hydrogen	No chemical formulas	Chemical formulas mostly incorrect	Chemical formulas somewhat correct	Chemical formulas mostly correct	Chemical formulas completely correct
Draw how water molecules decompose into oxygen and hydrogen molecules	No drawings or drawings are not relevant	Molecules were incorrectly depicted	Molecules were correctly depicted, but reaction process was not shown	Molecules were correctly depicted and reaction process was mostly correct	Molecules were correctly depicted and reaction process was completely correct

Instructions for the Electrolysis Demonstration

1. Prior to the demonstration do the following:
   a. Gather two wooden pencils, a pencil sharpener, a large beaker or trough, salt, two clip leads, a 9-volt battery, and two test tubes (optional).
   b. Remove the erasers and their metal sleeves from both pencils, and then sharpen both ends of both pencils.
2. The electrolysis is performed by attaching electrodes to a solution of salt water. During the class do the following and explain each step as you carry it out:
   a. Fill the beaker or trough with warm water, and then sprinkle a spoonful of salt in it.
   b. Attach the clips on one end of the wires to the electrodes on the battery. Attach the clips on the other ends of the wires to the tips of the pencils.
   c. Hold the opposite tips of the pencils in the water, so that the tips are fully underwater but are not touching the bottom. Wait for a minute or so and have students observe what happens.
   d. You may want to show students how the gases can be collected with test tubes. Fill the test tubes with water and position them over the two places where bubbles are coming up from the pencil tips in the water. One test tube will rapidly fill with gas and the other will fill more slowly.

IN-DEPTH INVESTIGATION: ELECTROLYSIS

READING: A New Way to Decompose Compounds

When Humphry Davy was alive, chemists had established that there were fundamental substances in nature, which they called elements. They believed that the elements were the building blocks of matter, and that they could exist in their elemental form or they could combine with other elements to form additional substances called compounds.

The properties of compounds often had no similarity to the properties of the elements that they contained. Therefore, chemists could not predict if a particular substance was an element or a compound. The criteria that chemists used to classify a substance were experimental—they would attempt to break down, or decompose, the substance in the lab.

Substances that decomposed were classified as compounds, and chemists could often chemically extract elements from the decomposition. Chemists had to test each decomposition product, however, because the decomposition of a compound could in some cases result in a compound and an element or two compounds. Substances that did not decompose were classified as elements.

The discovery of elements was impacted by the development of new laboratory techniques. When Davy tried out the newly invented battery in the lab, he found that it could be used to decompose substances. This technique was called electrolysis. By testing substances with a battery, Davy found that some substances that had previously been classified as elements were in fact compounds. Davy then identified new elements from the decomposition of these compounds.

LABORATORY DEMONSTRATION: Electrolysis

You've learned how Davy used batteries in a method called "electrolysis" to chemically separate elements from compounds. In this demonstration, you'll observe this process as your teacher will use a battery in an attempt to decompose water.

Procedure

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

1. Put on safety glasses.
2. Predict if water will be decomposed into new substances by the battery current. Explain the reasoning for your prediction.
3. Examine the electrolysis demonstration setup carefully and listen to your teacher's explanation of the different parts of the setup.
4. When your teacher begins the electrolysis, observe and record your observations.
5. Discuss your observations with the rest of the class.

Questions

1. Using the evidence you observed during the demonstration, would you say that water is a compound (can decompose) or an element (cannot decompose)? Explain the reasoning for your conclusion.
2. During the electrolysis gases formed at the two pencil ends. Do you think these two gases are the same? Why or why not?
3. Do you think either of the two gases that formed at the two pencil ends is air? Why or why not?
4. Do you think either of the two gases that formed at the two pencil ends is water vapor? Why or why not?
5. Imagine that in a follow-up experiment, an experimenter tested the gases that formed at the two pencil ends. These tests showed that both gases did not break down into any other substances. Are the gases compounds or elements? Explain the reasoning for your conclusion.
6. Measurement of the volume of the two gases produced when water decomposed showed that the amount of one gas produced was exactly double the amount of the other gas produced. Propose a reason that might account for this observation.
7. It is now known that water is composed of molecules, and each molecule contains one atom of oxygen and two atoms of hydrogen. The two gases produced during electrolysis are the elements oxygen and hydrogen; each is composed of two-atom molecules. Based on this information, what are the chemical formulas of water, oxygen, and hydrogen?
8. Draw a picture showing the process of decomposition of two water molecules at the atomic level. Show the atomic arrangements of water, oxygen, and hydrogen in your picture.

TEACHER NOTES

IN-DEPTH INVESTIGATION: WHAT HOLDS MATTER TOGETHER?

Context

In *Humphry Davy: Chemistry's First Showman*, Davy's use of a battery to decompose compounds leads him to propose a startling idea. He proposes that since electricity can be used to *un-bond* matter, then perhaps it is electricity that bonds matter together. In other words, electricity is the glue that links the particles of matter.

Overview

Students read a brief summary of the discoveries that determined the electrical nature of atoms and validated Davy's proposal that electricity is an essential property of matter. Students then read how chemical bonds are the outcome of the electrical nature of atoms.

Next Generation Science Standards Alignment

Science and Engineering Practices

1. Asking Questions and Defining Problems
   - Ask questions to clarify additional information and relationships.

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.

6. Constructing Explanations and Designing Solutions
   - Apply scientific ideas and evidence to provide an explanation of phenomena.

Disciplinary Core Ideas

- The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms.
- Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.

Crosscutting Concepts

- Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena.

Performance Expectations

- Structure and Properties of Matter HS-PS1-3: Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.

Understanding Goals

Students should understand:

- There are two types of electric charge: negative charge and positive charge.
- Electric charge is associated with subatomic particles. Protons have positive electric charge and electrons have negative electric charge.
- Chemical bonds are bonds that form between two atoms.
- Intermolecular bonds are bonds that form between two molecules, which are small groups of atoms chemically bonded together. Intermolecular bonds are much weaker than chemical bonds.
- The strength of chemical and intermolecular bonds varies depending on the identities of the elements and molecules.
- Forming bonds releases energy and breaking bonds requires an input of energy.

Student Materials

You will find on the following pages a reading and student instructions for planning and conducting an investigation.

Laboratory Experiment Facilitation

- Encourage students to suggest all their ideas about possible ways to compare the strength of the intermolecular bonds in the three liquids: water, rubbing alcohol and vegetable oil.
- When students plan their experiments, explain if their choices are limited due to availability of materials or safety equipment.
- Review students' experimental plans and suggest any necessary changes.
- For any experiments that students carry out, ensure that all necessary safety precautions are taken.
- Circulate around to students as they work on their experiments.
- A boiling point lab is one possible experiment that students can carry out if your room is properly equipped. Four other possible experiments follow.
  - *Surface tension with a penny*: Gather 3 pennies, a disposable pipette, paper towels, and small plastic cups with samples of each liquid. Place the penny head side up on a paper towel. Using the pipette, gently squeeze droplets of water onto the penny and count how many droplets the penny will hold. Dry the penny with the paper towel and squeeze all the liquid out of the pipette. Repeat first with rubbing alcohol and second with vegetable oil. (Note: It is important to test the liquids in this order.)
  - *Surface tension with glass tubes*: Gather a shallow dish and a narrow glass tube. Place about 20 mL of liquid in the shallow dish. Position the glass tube just below the level of the liquid in the dish and see how high the liquid rises. Repeat for the other liquids, taking care to wash and dry the dish and tube well when you change liquids. Dispose of liquids as directed.

- *Evaporation without heat source*: Gather three evaporating dishes, a 10-mL measuring cylinder, and fine point permanent marker, and an eraser. Pour 10 mL of each liquid into an evaporating dish. Use the marker to carefully mark the level of the liquid on the outside of the dish in two places. Place the dishes in a warm or sunny spot and observe the level of liquid every ten minutes for as long as you can (60 minutes is ideal). When done, dispose of liquids as directed. Wash the evaporating dishes. To remove the marker from evaporating dishes, rinse the outside of the dish and scrub gently with the eraser.
- *Evaporation with a heat source*: Obtain a hot plate, enough aluminum foil to cover the heating surface, a disposable pipette, and small plastic cups with samples of each liquid. Cover the top of the hot plate with aluminum foil. Crimp the edges so that the foil is secure to the top of the hot plate. Turn the hot plate to 8 and wait about 5 minutes for the hot plate to warm up. With no overlap, place a small drop each of water, rubbing alcohol, and vegetable oil on the foil. Time how long it takes for each drop to evaporate. Stop at 5 minutes. Carefully observe any residue from the drops.

Laboratory Experiment Rubric

Criteria	Not evident	Limited	Developing	Competent	Accomplished
Describe properties of a liquid related to bonds between molecules	No properties described	Properties described are not measurable	One measurable property described, but it does not relate to bonds between molecules	One measurable property described, and it relates to bonds between molecules	Two measurable properties described, and both relate to bonds between molecules
Plan an experiment and decide on types, how much, and accuracy of data needed	Did not plan an experiment	Experiment plan was incomplete or not doable as written	Experiment plan included safety, procedure steps, and materials, but it did not indicate how to collect the data needed to compare bond strengths	Experiment plan included safety, procedure steps, and materials, and it partially indicated how to collect the data needed to compare bond strengths	Experiment plan included safety, procedure steps, and materials, and it fully indicated how to collect the data needed to compare bond strengths
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

IN-DEPTH INVESTIGATION: WHAT HOLDS MATTER TOGETHER?

READING: Electricity and Matter

In *Humphry Davy: Chemistry's First Showman*, Davy uses electricity from a battery to decompose compounds. In this process, the electric current is pulling atoms away from each other. In thinking about this process, Davy wonders if electricity could also be the force that holds atoms together, an idea that had not been considered before. In the episode, Davy asks this question:

> *"Is electricity an essential property of matter?"*

Davy's idea was revolutionary. But it would take more than a century to figure out electricity's role in matter. In 1897, J. J. Thomson began a series of experiments that led to the discovery of electrons— very small particles with negative electric charge. Thomson proposed that these particles were pieces of atoms. Until this discovery, scientists had thought that atoms were indivisible. Now it seemed that atoms were made up of even smaller particles.

Ernest Rutherford followed up on Thomson's discovery by carrying out experiments into radioactivity and the structure of the atom. Atoms are neutral, so Rutherford knew that the atoms must also contain positive charge, in order to the balance the negative charge. In 1911, scientists working for Rutherford gathered experimental evidence that atoms have small dense positive nuclei. In 1920, Rutherford proposed that the nucleus of each atom contains both positive particles, called protons, and neutral particles, called neutrons. The existence of both particles was later verified experimentally.

The discovery of subatomic particles with negative and positive electric charge validated Davy's prediction that electricity is an essential property of matter. Electricity is indeed the "glue" that holds matter together. Because of their electrical nature, atoms interact with each other and form bonds. There are two kinds of bonds:

- Chemical bonds are bonds that form between two atoms.
- Intermolecular bonds are bonds that form between two molecules, which are small groups of atoms chemically bonded together. Intermolecular bonds are much weaker than chemical bonds.

When bonds form, energy is released because the new configuration is more stable. Conversely, breaking bonds requires an input of energy. An example of breaking chemical bonds is Davy's use of the battery. When energy is added to a compound by the battery, the compound undergoes a chemical reaction and decomposes into elemental substances.

LABORATORY EXPERIMENT: Compare Bond Strengths

Bonds vary in strength depending on the identity of elements or molecules. In this activity, you will work with a group to plan and conduct an investigation to compare the strength of the intermolecular bonds in three liquids: water, rubbing alcohol, and vegetable oil. Complete the following steps:

1. Consider what properties of a liquid are related to the strength of its intermolecular bonds. Share your ideas with the class.
2. Think about ways to gather data to compare the strength of intermolecular bonds in the three liquids. Share your ideas with the class.
3. Plan an investigation to compare the strength of the intermolecular bonds in the three liquids. In your plan, decide on types, how much, and accuracy of data needed to produce reliable measurements that will compare the strength of the intermolecular bonds. Also select appropriate tools to collect, record, analyze, and evaluate data. Be sure to carefully record your plan and to include safety notes. *Note: Your choices may be constrained by the availability of materials.*
4. Review your investigation plan with your teacher.
5. Carry out your investigation and collect your data.
6. Evaluate the success of your investigation and summarize what you learned about the strength of the intermolecular bonds in the three liquids.

WEB RESOURCES

Short Biography of Humphry Davy
http://www.chemheritage.org/discover/online-resources/chemistry-in-history/themes/electrochemistry/davy.aspx
This Chemical Heritage Foundation site contains a concise biographical sketch and images of Davy.

Short Scientific Biography of Humphry Davy
http://scienceworld.wolfram.com/biography/Davy.html
This site contains a concise but very complete listing of Davy's scientific accomplishments.

Humphry Davy, Self-Made Chemist
http://pubs.acs.org/subscribe/archive/tcaw/13/i04/pdf/404chronicles.pdf
This American Chemical Society article contains a longer biographical sketch of Davy that describes both his life and scientific accomplishments.

Science and Celebrity: Humphry Davy's Rising Star
http://www.chemheritage.org/discover/media/magazine/articles/26-4-science-and-celebrity.aspx
This Chemical Heritage Foundation article describes the background and content of Davy's public demonstration of electrolysis using a voltaic battery.

On hybrid objects and their trajectories: Beddoes, Davy and the Battery
http://rsnr.royalsocietypublishing.org/content/63/3/247
In this detailed and complex Royal Society article, the "hybrid object" is the voltaic battery. The article explores how experimentation with the voltaic battery at the Pneumatic Institution had a wide-ranging impact on multiple expert communities of that time.

Excerpt from *Age of Wonder*, by Richard Holmes
www.npr.org/templates/story/story.php?storyId=104874609
Richard Holmes wrote the award-winning book *Age of Wonder,* a series of portraits of the men and women of science in the Romantic era. This excerpt introduces the main themes of the book and describes how the "second scientific revolution" of the Romantic era was inspired by a series of breakthroughs in the fields of astronomy and chemistry.