The Mystery of Matter: Search for the Elements

TEACHER'S GUIDE

Introduction

The Mystery of Matter: Search for the Elements is a three-hour PBS series that brings to life seven extraordinary scientists who addressed one of the most important questions in the history of science: *What is the world made of?*

The series introduces viewers to **Joseph Priestley** and **Antoine Lavoisier,** whose discovery of oxygen—and radical interpretation of it—led to the modern science of chemistry; **Humphry Davy,** who made electricity a powerful new tool in the search for elements; **Dmitri Mendeleev,** whose Periodic Table brought order to the growing gaggle of elements; **Marie Curie,** whose groundbreaking research on radioactivity cracked open a window into the atom; **Harry Moseley,** whose exploration of atomic number redefined the Periodic Table; and **Glenn Seaborg,** whose discovery of plutonium opened up a whole new realm of elements, still being explored today.

This groundbreaking program reveals not only *what* these scientists discovered but also *how*, skillfully weaving together re–enactments of their discoveries shot with replicas of their lab equipment; host scenes and narration; commentary by scholars, and the scientists' own words delivered by Broadway-caliber actors.

In *The Mystery of Matter*, science is shown as it happens, revealing the ways scientists work as they generate ideas and experiments. The program profiles people who became scientists because they were passionate about understanding nature, and who persevered through setbacks to make astonishing discoveries. The program also vividly shows that these scientists were individuals who had different personal, ethical, cultural, and political concerns, and who, like all people, were deeply influenced by the context in which they lived and worked.

What is the value of introducing *The Mystery of Matter: Search for the Elements* into the high school science classroom? Including the history of science in the teaching of chemistry can provide a clarifying framework for the different approaches scientists take to answering questions about the natural world – and how the scientific discoveries of one generation build on those of previous generations. Students will see that science is filled with colorful characters, miscues, triumphs and unlikely sources of inspiration. The "human story" behind the discovery of the elements can be used to draw students into learning the chemistry concepts involved, enhance their interest in chemistry, and impart a better understanding of the scientific endeavor. In addition, framing scientific knowledge in the context of a story can result in longer retention of the knowledge gained from the learning experiences.

The *Mystery of Matter* Teacher's Guide offers a wealth of resources meant to foster the use of the program in the high school chemistry classroom. These resources include an index and searchable transcript of the program; alignments of the program to both the NRC National Science Education Standards and the Next Generation Science Standards; suggestions for student reflection on sections of the program; classroom investigations related to the program; web resources, and a glossary.

Components and Use

The PBS series is three hours long and consists of six main sections, each one centered on an important idea related to matter. For each of the six program sections, the Teacher's Guide includes the following components:

Script. Each speaker's words are shown and labeled with his or her name: host, narrator, scholar or character. Descriptions of the images on screen at that moment are also included in *italicized text*.

Standards Alignment. The script for each section is subdivided into chapters, and each chapter begins with a description of how it aligns with the NRC's National Science Education Standards and the Next Generation Science Standards (NGSS).

Embedded Icons, Margin Notes, and Highlights. Each script includes embedded point-of-use icons, margin notes, and highlights. These point-of-use features are:

- **Stop & Think** icons provide questions teachers can put to students to stimulate their thinking. Teachers can ask these questions immediately by pausing the program or later when the program is complete.
- **Everyday Applications** provide brief descriptions of modern applications. These descriptions can be presented immediately by pausing the program or later when the program is complete.
- **Notes from the Field** include examples of ideas for incorporating the program into your teaching, ways teachers successfully made modifications, or suggestions for promoting classroom discussion.
- **Margin Notes** of chemistry-content keywords show where specific concepts are explored. The level of exploration of the concept is shown by the titles Concept in Brief (highlighted in light blue), Concept in Detail (highlighted in dark blue), and Example of Science Practice (highlighted in orange).
- **Glossary** terms within the program text are highlighted.

Activity Ideas. Each section has a list of Web-based and hands-on short activities for students that are related to the program, each leading to further understanding of the science concepts with which the scientist is concerned. Each activity includes brief instructions and/or a link to a website.

In-Depth Investigations. One or two In-Depth Investigations are presented with complete student and teacher print materials, including readings and NGSS alignment notes, and can be immediately implemented in the classroom. The In-Depth Investigations specifically relate to and refer to the section content and expand on one of the important concepts presented in the section, in order to support understanding of the big ideas presented in the section.

Web Resources. This resource includes websites and applets that relate to the life and work of the principal scientist of the section, the concepts presented, and the corresponding time in history. One possible use of the Web Resources is student research.

The Teacher's Guide also includes a glossary and a list of main concepts, noting in which section of the series they are introduced or developed.

Next Generation Science Standards

Some states have recently adopted the Next Generation Science Standards (NGSS). The NGSS are presented in the form of student performance expectations that reflect the interconnected nature of science. Each student performance expectation integrates three important dimensions of science and engineering: practices, disciplinary core ideas, and crosscutting concepts.

The student performance expectations clarify what students are expected to know and be able to do by the end of the grade or grade band. However, the intent of the NGSS is that schools will provide additional opportunities for students to engage in the three dimensions of science and engineering.

The In-Depth Investigations that accompany each section of the Teacher's Guide are written to align with the NGSS. The table that follows describes how each In-Depth Investigation aligns with the science and engineering practices and with the student performance expectations.

***Table**: Alignment of In-depth Investigations with NGSS*

Title	Science and Engineering Practices	Performance Expectation
Section 1: Back to the 1700s	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.	

Section 1: Theories of Combustion	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.	Chemical Reactions HS-PS1-7: Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.
Section 2: Electrolysis	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.	
Section 2: What Holds Matter Together?	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. 3. Planning and Carrying Out Investigations: 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.	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.

Section 3: Organizing the Elements	2. Developing and Using Models: Use a model based on evidence to illustrate the relationships between components of a system. 5. Using Mathematics and Computational Thinking: Use mathematical, representations of phenomena to support explanations. 6. Constructing Explanations and Designing Solutions: Apply scientific reasoning, theory, and models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.	
Section 3: Predicting Reaction Products	2. Developing and Using Models: Use a model based on evidence to illustrate the relationships between components of a system. 5. Using Mathematics and Computational Thinking: Use mathematical, representations of phenomena to support explanations. 6. Constructing Explanations and Designing Solutions: Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources (including students' own investigations, models, theories, simulations, peer review) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.	Chemical Reactions HS-PS1-2: Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.
Section 5: Atoms and X-rays	2. Developing and Using Models: Use a model based on evidence to illustrate the relationships between systems or between components of a system. 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. 6. Constructing Explanations and Designing Solutions: Apply scientific reasoning and models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation 7. Engaging in Argument from Evidence: Evaluate the evidence and reasoning behind currently accepted explanations to determine the merits of arguments.	

Section 6: Nuclear Power	7. Engaging in Argument from Evidence: Compare and evaluate competing arguments in light of currently accepted explanations and new evidence.	HS-ESS3-2: Evaluate competing design solutions for developing energy resources based on cost-benefit ratios.
Section 6: Modeling the Nucleus	2. Developing and Using Models: Develop a model based on evidence to predict the relationships between systems or between components of a system. 5. Using Mathematics and Computational Thinking: Use mathematical representations of phenomena to describe and support explanations. 6. Constructing Explanations and Designing Solutions: Apply scientific reasoning and models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion. 7. Engaging in Argument from Evidence: Evaluate the evidence and reasoning behind currently accepted explanations to determine the merits of arguments.	HS-ESS3-2: Structure and Properties of Matter HS-PS1-8: Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.

Summary of the Program Sections

The three-hour PBS series consists of six sections. With the exception of the first story, **Oxygen: The Gas that Changed Everything** (which features two scientists), each section focuses on one of the seven scientists featured in the series and explores an important idea related to matter.

1. Oxygen: The Gas that Changed Everything

Oxygen: The Gas that Changed Everything chronicles a remarkable scientific duet between two of the most memorable figures in the history of chemistry: a happy-go-lucky British minister named Joseph Priestley and an analytical French tax administrator named Antoine Lavoisier. The story begins with discovery of carbon dioxide in 1754 – a discovery that reveals there is another whole state of matter to explore: gases. Throwing himself into this new field, Priestley discovers nine new gases, becoming the world's leading authority on the subject. Inspired by a visit to a local brewery, he invents a method for making soda water: carbonation. And when a French industrial spy passes on the mistaken idea that soda water might be a cure for scurvy, Lavoisier takes an interest in the new field.

Lavoisier immediately senses the new field of gases has the potential to bring about a scientific revolution. He quickly discovers that when a metal rusts, or forms what is then called a "calx," it *gains* weight by absorbing something from the air – just the opposite of what chemistry's prevailing theory says. But for two years Lavoisier searches in vain for the identity of this mystery gas.

Meanwhile, back in England, Priestley has been experimenting with a curious substance called the red calx of mercury. When heated, it turns into liquid mercury and gives off a gas. Priestley tests the gas, expecting it to be carbon dioxide, which would put out a candle. But to his surprise, this gas makes candles burn brighter and longer than ordinary air.

Two months later, on a visit to Paris, Priestley reports his discovery over dinner with Lavoisier. Thinking this might be the mystery gas he's been looking for, Lavoisier hurries to the local apothecary to buy his own sample of mercury calx. Six months later (without mentioning Priestley's revelations over dinner), Lavoisier announces his discovery of this remarkable new gas, which he soon names "oxygen."

Even today, Lavoisier is criticized for failing to acknowledge his debt to Priestley. But Lavoisier goes on to make oxygen the foundation of a whole new chemistry, showing that air is a mixture of two newly discovered gases (oxygen and nitrogen); that water is a compound of two gases (oxygen and hydrogen), and that fire is not an element, as the ancients believed, but a *process* of chemically combining with oxygen. Finally, Lavoisier shows that rocks of every conceivable variety might harbor undiscovered elements chemically fused with oxygen – thereby setting off a worldwide race to discover new elements.

2. Humphry Davy: Chemistry's First Showman

Humphry Davy: Chemistry's First Showman features one of the men soon caught up in the race to discover new elements. A precocious chemist from the remote seaside village of Penzance, Humphry Davy is a fearless experimenter. Hired by an institution to explore the potential health benefits of newly discovered gases, he tries each of them on himself, nearly killing himself more than once. This experimentation leads to his discovery of "laughing gas," which becomes a popular form of entertainment across England.

While still in his early 20s, Davy becomes a "rock star" at London's new Royal Institution, dazzling audiences with popular lectures that often feature spectacular demonstrations. The traffic jams of people coming to hear his lectures grow so bad that the street outside the institution becomes the first one-way street in London.

But Davy wants to be more than a showman, so in 1806 he seizes on the recently invented battery, hoping he can use it to pry substances apart and reveal the elements within them. He is spectacularly successful, discovering potassium one day, sodium the next, and then four more elements the following year. All over Europe, other chemists seize on his technique, sending the number of elements even higher.

More important, Davy senses that electricity might be the very glue that holds all the particles of matter together. In the 17th century, electricity had been little more than a party trick – something people used to shock each other or make each other's hair stand on end. Davy shows that electricity is an essential property of matter – one that would be a central feature of science from then on.

3. Dmitri Mendeleev: Chemistry's Improbable Savior

The third section of the series addresses scientists' efforts to find an order among the growing number of elements that have been discovered. *Dmitri Mendeleev: Chemistry's Improbable*

Savior opens in the year 1869, when there are 63 known elements. For years, chemists have disagreed about even the most basic thing about these elements: the amount an atom of each element weighs – its "atomic weight." After the first-ever international chemistry conference, held in Karlsruhe, Germany, in 1860, leads to a new, uniform system of weights, a number of scientists set out to organize the elements, sensing there is a hidden mathematical order among them. But no one can quite put the puzzle together.

At the time, Western Europe is the center of scientific thought was, so it's surprising when the solution finally comes from a young Russian chemistry professor. Dmitri Mendeleev doesn't set out to be chemistry's savior. He's simply trying to organize the introductory chemistry textbook he's writing. But as he grapples with this challenge over one weekend in 1869, he makes a discovery for the ages: the Periodic Table of the Elements.

This section shows how Mendeleev examines the elements in multiple ways, arranging them in order of increasing atomic weight but also keeping in mind their chemical properties, occasionally skipping a spot or reversing two elements to keep them aligned with other members of their "chemical families."

Mendeleev believes his table reveals a law of nature: that the properties of the elements are determined by their atomic weights and vary in a regular, periodic way across the table. His confidence in the Periodic Law gives him the courage to make precise predictions about three "missing elements" for which he's left room in his table. When all three elements are discovered in the next 15 years, having just the properties Mendeleev predicted, his reputation is assured. Today the Periodic Table is one of the most iconic images in all of science, embracing all the fundamental ideas of chemistry in a single chart.

4. Marie Curie: Unlikely Revolutionary

One of the most compelling personal stories in science – and an even more unlikely revolutionary than Mendeleev – is featured in the program's fourth section. *Marie Curie: Unlikely Revolutionary* introduces viewers to the person who would fundamentally change our understanding of matter – a Polish graduate student named Maria Sklodowska.

Maria has come to France to study science and escape the brutally repressive conditions in Russian-ruled Poland. At the time, Paris is one of the few places in the world where women can attend university. Driven by her passion for science, Sklodowska enrolls in physics at the Sorbonne and graduates first in her class. She soon meets and marries another young scientist, Pierre Curie, and from then on is known as Marie Curie.

Searching for a subject that will allow her to earn a doctorate in science—the first woman to do so in France—Marie decides to tackle the recently discovered rays given off by the element uranium. With Pierre's assistance, Marie soon learns these mysterious rays are not unique to uranium but reflect a more general property of matter – what she calls "radioactivity." She goes on to identify two new elements – polonium (named for her native country) and radium – and shows how radioactivity can be used to find other new elements. For this work, Marie wins the 1903 Nobel Prize in Physics, sharing it with Pierre and the co-discoverer of radioactivity, Henri Becquerel. She goes on to win a second Nobel (in chemistry) all her own. She is still the only woman to win two Nobel Prizes.

More importantly, Marie's investigation of radium reveals that the element glows in the dark, signaling an unknown source of energy *within* the atom. This observation leads others around the world to investigate the nature of the atom itself, eventually discovering the atom's internal pieces and how they fit together.

5. Harry Moseley: Numbering the Elements

Harry Moseley: Numbering the Elements begins in 1897 with J.J. Thomson's discovery of the electron — a negatively charged particle much smaller than the atom and a universal constituent of matter – a part of every atom. This discovery raises two key questions: First, since the electron weighs almost nothing, where is the atom's mass? And second, where is the positive charge needed to offset the negative electron and keep atoms electrically neutral?

The program's fifth section focuses on one of the many young scientists drawn to Manchester to pursue these questions under physicist Ernest Rutherford: Henry Gwyn Jeffreys Moseley, known as Harry to his friends. Moseley, 22, has just arrived at Rutherford's lab in 1910 when he witnesses one of the pivotal experiments in the history of science: the gold foil experiment. Under Rutherford's supervision, graduate students Hans Geiger and Ernest Marsden bombard a thin sheet of gold foil with positively charged alpha particles. Most of the particles pass straight through the foil, but to their surprise, Marsden and Geiger find that a small number bounce almost straight back in their faces. The experiment shows that the atom's positive charge, and most of its mass, lie at the center of the atom, concentrated in what Rutherford names the "nucleus," while most of the atom is empty space.

In 1912, Moseley turns his attention to some exciting news out of Germany: X-rays – the wondrous rays whose discovery so excited the world 15 year earlier – can be split up, or "diffracted," into different wavelengths or frequencies, in much the way light can be divided into different colors by a prism. Seizing on this new tool, Moseley discovers that each element has a unique X-ray spectrum that can be used, like a fingerprint, to identify each element.

To his surprise, when he compares the X-ray spectra of ten neighboring elements in the Periodic Table, Moseley finds that their dominant X-ray lines rise in frequency, step by step, forming an image that comes to be known as "Moseley's staircase." The only possible explanation for this remarkable regularity, he says, is that the positive charge on the nucleus increases by a single unit from one element to the next. Building on Moseley's work, Rutherford soon discovers the piece of the atom responsible for this charge – the proton – and shows that each element is defined by the number of protons in its nucleus – its atomic number. Together, Moseley and Rutherford redefine the Periodic Table, showing that it is actually organized by atomic number, not atomic *weight*, as chemists have believed ever since Mendeleev.

Harry Moseley: Numbering the Elements ends in tragedy when Moseley enlists to fight in World War I in 1914. A year later he is killed by a sniper's bullet in the battle of Gallipoli. Moseley's death at age 27 not only deprives the world of a brilliant scientist but also prompts England and all other counties to rethink the role of scientists in war. Ever since then, most scientists have been asked to serve their countries by doing research far from the front on things like code-breaking, radar and the atomic bomb.

6. Glenn Seaborg: Venturing Beyond Uranium

The sixth and final section of the series, *Glenn Seaborg: Venturing Beyond Uranium,* is set in the United States. It begins on the eve of World War II, with the 1939 announcement that German chemists have split the uranium atom by bombarding it with neutrons, a process called “atomic fission.” The protagonist of this section, Glenn Seaborg, is then a 26-year-old chemistry instructor at the University of California, Berkeley. He has conflicting responses to the news of fission: thrilled to hear about this scientific discovery ... but chagrined he has missed the chance to make the discovery himself.

Around the world, thoughts turn immediately to the possibility of harnessing fission to create an atomic bomb. But what interests the young Berkeley chemist is the fact that the German discovery has debunked Italian physicist Enrico Fermi’s claims to have created elements beyond uranium, element 92. Suddenly, there’s a second chance to be the first to create “transuranic” elements. Following up on the work of Berkeley physicist Ed McMillan, who creates element 93 (neptunium) in 1940, Seaborg creates element 94 – plutonium – in early 1941. And two months later, he establishes that it can be split by neutrons – the very property that makes uranium a potential fuel for an atomic bomb.

Soon after the Japanese attached on Pearl Harbor, Seaborg joins the Manhattan Project at the University of Chicago. Just 30 years old, he is put in charge of a team developing a process for separating plutonium from the other products of nuclear reactions. The process Seaborg’s team develops generates the plutonium that goes into the first atomic bomb, tested over the New Mexico desert in July 1945. Three weeks later, a second plutonium bomb destroys the city of Nagasaki, Japan, finally bringing the war to an end.

In 1951, Seaborg and McMillan share the Nobel Prize in Chemistry. By that time, Seaborg has already gone on to create more new transuranic elements. And around the world today, scientists continue the quest to create new elements, using technique likes those Seaborg pioneered.