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# **O<sub>2</sub>XYGEN**



## **Oxygen Symposium**

Wisconsin Initiative for Science Literacy  
Department of Chemistry  
University of Wisconsin-Madison  
Saturday, March 29, 2003  
9:00 a.m. to 4:30 p.m.

## Welcome

Welcome to the Oxygen Symposium. Our program today will deal with oxygen's discovery as well as current research on oxygen, ranging from its role in aging to its potential to produce cleaner industrial processes. Between talks we will dramatically – and sometimes noisily – demonstrate unique properties of this fascinating element.

We at the **Wisconsin Initiative for Science Literacy (WISL)** are excited to bring you this symposium. **WISL** has a special interest in encouraging scientists, artists and humanists to explore the common creative thrusts and overlapping aspects of their disciplines. We are excited that other campus events also have been synchronized this spring to celebrate oxygen and its discovery. The University Theatre is staging the play *OXYGEN* and the UW Memorial Library is displaying very rare chemistry texts of the original discoverers of oxygen.

The play *OXYGEN*, being offered through April, revolves around which of three famous scientists of the 1700s – Joseph Priestley, Antoine Lavoisier or Carl Wilhelm Scheele – can truly lay claim to discovery of the essential gas. The play not only tackles an historical question but also examines the culture of research and the creativity involved in “doing science.” The playwrights, Carl Djerassi and Nobel Laureate Roald Hoffmann – both eminent chemists – are with us here today and exemplify the rich results that can spring from a merger of arts, humanities and sciences.

Through April, the Memorial Library will share with the public several texts from its rich collection of historical books and treatise on alchemy and early chemistry. The books will be on display in Rm 976 and will include works by Priestley and Scheele, and Lavoisier's own copy of his influential book on chemistry printed in 1793. The library also has on display the various literary works of the playwrights Djerassi and Hoffmann.

And in keeping with our multidisciplinary theme, Prof. Marc Fink and members of the Pro Arte Quartet will entertain us today with a brief sample of music by Mozart, a contemporary of the discoverers of oxygen. It's a piece that the aristocratic Madame and Monsieur Lavoisier might have enjoyed with their friends after a hard day in the lab.

As you can see from these events, our approach at the **Wisconsin Initiative for Science Literacy** is not always conventional. But our focus always is clear in promoting literacy in science, mathematics, and technology among the general public. Some of our current programs include “Science Saturdays” for middle schoolers and their parents; “Conversations in Science” between middle and high school teachers and UW faculty; and “Capitol Science,” offering elected officials and staff insights into the impact of new science and technology developments on society. Soon we will begin “Conversations in Creativity,” jointly sponsored by **WISL**, the Arts Institute, and the Center for Humanities of UW-Madison. And this fall we will bring Dava Sobel, author of *Galileo's Daughter* and *Longitude*, to campus.

For more on these and other **WISL** activities, see our website: [www.scifun.org](http://www.scifun.org). We hope you enjoy your day with us and will participate in other **WISL** programs.

Bassam Z. Shakhashiri

## WISCONSIN INITIATIVE FOR SCIENCE LITERACY

The Wisconsin Initiative for Science Literacy is a national program with two goals: to promote literacy in science, mathematics, and technology among the general public and to attract future generations to careers as the researchers, entrepreneurs, and teachers on whom the nation's continuing economic health and national security will depend. Society makes progress in addressing critical issues by having both a skilled, creative, and productive workforce and a citizenry able to judge the risks and enjoy the benefits of advances in science and technology. The Initiative seeks to boost opportunities for educational success for *all* students, especially those from under-represented groups, and to empower adults to participate responsibly in our cherished democratic institutions. The Initiative aims to enhance the development of talent for careers in science and in science teaching and to advance the level of appreciation of science among the non-practitioners who are its beneficiaries. The Initiative explores and celebrates the intellectual and emotional links between science, the arts, and the humanities.

Bassam Z. Shakhashiri, Director  
Rodney Schreiner, Senior Scientist  
Laurens Anderson, Honorary Fellow  
Jean M. Lang, Senior Writer/Editor  
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### On the Cover

*Portrait of Monsieur Lavoisier and His Wife*, by Jacques Louis David, painted in 1788. The painting is 264 cm × 224 cm (8 ft 6 in × 7 ft 4 in) and is in the collection of the Metropolitan Museum of Art, New York.

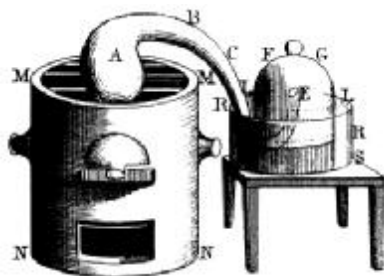
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**Oxygen**  
**A Public Symposium**  
**Saturday, March 29, 2003**  
**Rm 1351 Chemistry Bldg.**  
**9:00 a.m. to 4:30 p.m.**

**Program of the Day's Events**

- 9:00 Introductory Remarks** — Prof. Bassam Z. Shakhashiri, director of the Wisconsin Initiative for Science Literacy, and William T. Evjue Distinguished Chair for the Wisconsin Idea; and Prof. John C. Wright, Chair of the Department of Chemistry and Andreas Albrecht Professor of Chemistry, UW-Madison.
- 9:15 “Where Did Oxygen Come From?”** — Prof. Patricia Kiley, Professor, UW-Madison Dept. of Biomolecular Chemistry.
- 9:35 Discussion**
- 9:45 Demonstration 1** — Peroxides, oxygen and combustion.
- 9:55 “The Birth of Oxygen: Untangling the Web”** — Prof. Alan Rocke, Dept. of History, Case Western Reserve University.
- 10:15 Discussion**
- 10:25 Demonstration 2** — Reactions of oxygen with glucose and dyes — Prof. Laurens Anderson, UW-Madison Dept of Biochemistry
- 10:35 15- Minute Break** ( Refreshments outside Rm 1351 )
- 10:50 “Marvelous Biological Control of the Reactivity of Molecular Oxygen”** — Prof. Brian Fox, UW-Madison Dept. of Biochemistry.
- 11:10 Discussion**
- 11:20 Demonstration 3** — Profs. Marc Fink, David Perry, Richard Blum, and Parry Karp perform the first movement of Quartet for Oboe and Strings, K. 370, by Mozart, a contemporary of Lavoisier, Priestley, and Scheele.
- 11:35 “Madame Lavoisier”** — Prof. Roald Hoffmann, Dept. of Chemistry and Chemical Biology, Cornell University.
- 11:55 Discussion**
- 12:05 Lunch Break** (1 hour, 25 minutes) — Box lunches, by advance reservation, are in Chemistry Bldg. lobby.



- 1:30 “Toward an Environmentally Friendly Chemical Industry: Selective Chemical Oxidation with Molecular Oxygen”** — Prof. Shannon Stahl, UW-Madison Dept. of Chemistry.
- 1:50 Discussion**
- 2:00 Demonstration 4** — Reactions of oxygen with metals.
- 2:10 “The Unmaking and the Making of Chemical Elements: The Chemistry of Salts in the 18th Century”** — Prof. Thomas Broman, UW-Madison Dept. of History of Science.
- 2:30 Discussion**
- 2:40 Demonstration 5** — Unusual properties of molecular oxygen.
- 2:50 15- Minute Break** (Refreshments outside Rm 1351)
- 3:05 “Oxygen and the Aging Process”** — Prof. Richard Weindruch, University of Wisconsin Medical School.
- 3:25 Discussion**
- 3:35 Demonstration 6** — Measuring oxygen inside and outside the body.
- 3:45 “How to Smuggle Science to the Public”** — Prof. Carl Djerassi, Dept. of Chemistry, Stanford University.
- 4:05 Discussion**
- 4:15 Concluding General Discussion**
- 4:25 Demonstration 7** — The thermite reaction: extracting molten iron from rust.
- 4:30 Adjourn**

Demonstrations are presented by Prof. Bassam Z. Shkhashiri and Dr. Rodney Schreiner, unless otherwise indicated.

## Speakers' Topics and Biographies

### Where Did Oxygen Come From?

**Patricia Kiley**  
**Professor, Department of Biomolecular Chemistry**  
**University of Wisconsin-Madison**

Humans, like many organisms on this planet, require molecular oxygen to generate energy, a necessity for life. This is why humans must breathe air (which contains about 21 percent oxygen) and why the heart must pump oxygenated blood from our lungs throughout our body. However, the earth's atmosphere did not always contain oxygen. Rather, life on this planet evolved in the absence of oxygen. It was not until the production of oxygen by the water-splitting enzymes of photosynthetic organisms, such as blue-green algae, that large amounts of oxygen appeared on Earth.

While humans maintain a strictly aerobic – or oxygen-dependent – lifestyle, it is important to realize that many other of the Earth's inhabitants have evolved to live in environments of various oxygen tensions. In particular, many bacteria, including some that cause disease, have the ability to adapt their metabolisms to the amount of oxygen that is present in their environment. In contrast, other bacteria do not use oxygen at all for energy generation but may survive short-term exposures to air. Understanding the metabolic strategies and regulatory schemes that allow cells to survive at different oxygen tensions has been an active area of research in biology. This research has the potential to uncover new approaches for eliminating disease-causing bacteria. It may also reveal ways to engineer other bacteria to make important drugs or chemicals.

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Patricia Kiley is a professor of biomolecular chemistry at the University of Wisconsin Medical School and her research focuses on cellular mechanisms for sensing molecular oxygen. Kiley received her undergraduate degree from the University of Massachusetts and her Ph.D. in Microbiology from the University of Illinois, Urbana-Champaign where she studied photosynthetic bacteria. She did postdoctorate work in the Department of Biochemistry at the University of Wisconsin where she began her studies on cellular oxygen-sensing mechanisms. Kiley joined the UW-Madison's Department of Biomolecular Chemistry in 1990 and her work has been recognized by several awards including the National Science Foundation's Young Investigator Award and the Shaw Scientist Award. The National Institute for Health has competitively funded her research since 1991.



Patricia Kiley

## The Birth of Oxygen: Untangling the Web

**Alan Rocke**  
**Professor, Department of History**  
**Case Western Reserve University**

The gas presently known as oxygen was discovered relatively simultaneously and relatively independently by three chemists of the late eighteenth century: the Frenchman Antoine Lavoisier in Paris, the Swede Carl Wilhelm Scheele in Uppsala, and the Englishman Joseph Priestley in Calne, Wiltshire. But what does the qualification “relatively” signify? There are chronological, geographical, theoretical, experimental, and personal issues relating to the question. The speaker will address some of these complexities regarding the history of the discovery of oxygen, and will attempt to arrive at a few moderately secure conclusions.

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Born in Chicago, Alan Rocke was educated at Beloit College and the University of Wisconsin, where he received the Ph.D. in History of Science in 1975. In 1978 he was hired as assistant professor at Case Western Reserve University in Cleveland, where he continues to teach today; his present title is Henry Eldridge Bourne Professor of History. His specialty is the history of European chemistry, especially French and German, and especially during the nineteenth century. In addition to many articles, he has published books on the history of atomic theory, the development of the theory of chemical structure in Germany, and the development of chemistry in nineteenth-century France. He has twice been a visiting scholar at the Max Planck Institute for History of Science in Berlin, has won the Dexter Prize of the American Chemical Society (History Division), and is a Fellow of the American Association for the Advancement of Science.



Alan Rocke



# Marvelous Biological Control of the Reactivity of Molecular Oxygen

**Brian G. Fox**  
**Professor, Department of Biochemistry**  
**University of Wisconsin-Madison**

It is widely acknowledged that molecular oxygen is an essential participant in the combustion of fuel substances, whether that be in a forest fire or in a car engine. This presentation will focus on the role of oxygen in central metabolic pathways of living organisms, which proceed by the controlled release of the energy of combustion. One important example is oxidative phosphorylation in which the energy released by the metabolization of food is made available to the cell. It is a reaction that proceeds with highest efficiency when molecular oxygen is present. By looking at the flow of electrons in biological electron transfer circuits, the importance of molecular oxygen as an oxidant can be more fully appreciated.

Discussion will focus as well on three different but important biological reactions that also require the participation of molecular oxygen as an oxidant. These are the synthesis of DNA, the biological cleanup of hydrocarbons such as might be released in an oil spill, and the conversion of saturated fats to unsaturated fats. Surprisingly, these apparently unrelated reactions are catalyzed by evolutionarily-related enzymes with similar three-dimensional structures. For DNA synthesis, molecular oxygen participates only indirectly by helping to create a reactive protein radical species. For hydrocarbon oxidation and unsaturated fat production, molecular oxygen is a more direct participant, but ends up with different fates upon completion of the reactions. This brief overview underscores the essential participation of molecular oxygen in many critically important biological reactions.

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Owing to an aversion to neckties and haircuts, Brian Fox realized many years ago as an undergraduate at Carleton College that he was more suited to academic research than becoming a barrister or broker. While associating with a ready crowd of bacteriologists, biochemists, and biophysicists during his graduate and postdoctoral studies at the University of Minnesota and Carnegie Mellon University respectively, he learned to appreciate the marvelous versatility and essential role of microbes in the metabolism of virtually all organic compounds found on Earth. This would include wood, sugars, fats, petroleum products, and many other substances. Since then, and as a Professor of Biochemistry at the University of Wisconsin-Madison, Fox has studied the ability of these simple organisms and their special enzymes to perform the most complex and demanding of chemical reactions at room temperature using the oxygen gas present in air to extract energy. His professional activities now focus on the enzymatic synthesis of nutritionally and economically valuable unsaturated fats, the biological oxidations of petroleum constituents, and the enzymatic modifications of explosives.



Brian G. Fox

## Madame Lavoisier

**Roald Hoffmann**  
**Professor, Department of Chemistry and Chemical Biology**  
**Cornell University**  
**(Co-author of the play *OXYGEN*)**

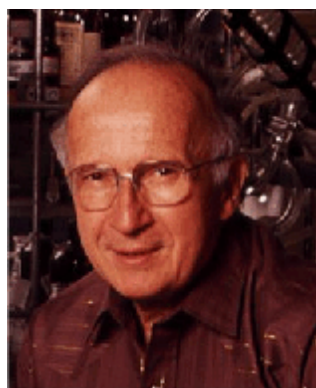
Marie Anne Pierrette Paulze Lavoisier deserves an opera. In a slide presentation, her remarkable life will be sketched (as she sketched the chemical experiments of her husband, M. Lavoisier) making use of extant images of the period.

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Roald Hoffmann, born in 1937 in Zloczow, Poland, is the Frank H. T. Rhodes Professor of Humane Letters at Cornell University in the Department of Chemistry and Chemical Biology. He has received many of the honors of his profession, including the 1981 Nobel Prize in Chemistry (shared with Kenichi Fukui) and the National Medal of Science. “Applied theoretical chemistry” is the way Roald Hoffmann likes to characterize the particular blend of computations stimulated by experiment and the construction of generalized models – frameworks for understanding – that is his contribution to chemistry. Roald Hoffmann also writes essays, nonfiction, poems and plays, and has been the presenter of a major Annenberg-CPB telecourse, “The World of Chemistry.” His fourth and most recent poetry collection, *Soliton*, was published in 2002 by Truman University Press.



Madame Lavoisier



Roald Hoffmann

## **Toward an Environmentally Friendly Chemical Industry: Selective Chemical Oxidation with Molecular Oxygen**

**Shannon S. Stahl**  
**Professor, Department of Chemistry**  
**University of Wisconsin-Madison**

The chemical industry has contributed significantly to the high quality of life that we enjoy in developed countries. Many useful chemicals, including pharmaceuticals, agrochemicals, and polymeric materials, are derived from petroleum feedstocks. The derivation often involves a process called selective oxidation, which in many cases involves the addition of oxygen atoms to specific locations in the petroleum molecules. Unfortunately, these selective oxidation reactions use specialized chemicals that have had major detrimental consequences for the environment, ranging from the release of PCBs into lakes and rivers to heavy metal contamination of ground water supplies.

An environmentally friendly solution to this problem is to use molecular oxygen, the form of oxygen found in the air, as the chemical oxidant, because the only by-product of the reaction is water. However, oxidation reactions involving molecular oxygen conjure up vivid images of explosions or flames shooting from a burning building, the detonation of gasoline in an automobile engine, the fire on a burner of a gas stove, or the notorious conflagration of the hydrogen-filled German zeppelin, Hindenburg. In these cases, the chemical reaction results in complete oxidation of the fuel to produce carbon dioxide and/or water. These oxidations release tremendous amounts of heat, and they are very difficult to control. Currently, research laboratories around the world are investigating new ways to control the chemistry of molecular oxygen through the use of catalysts. Taming the reactivity of oxygen will be a major step toward an environmentally friendly chemical industry.

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Shannon Stahl is a fourth year faculty member in the Department of Chemistry at the University of Wisconsin-Madison and his research group has been investigating new catalysts for selective oxidation chemistry with molecular oxygen. This work has been supported by funding from both governmental (National Science Foundation) and industrial sources (Dow Chemical Company, Merck Research Laboratories, and Abbott Laboratories). Shannon was an undergraduate at the University of Illinois at Urbana-Champaign (B.S., 1992). He subsequently attended the California Institute of Technology (Ph.D., 1997), where he studied the selective oxidation of methane to methanol catalyzed by platinum salts in water. From 1997-1999, he conducted postdoctoral research at the Massachusetts Institute of Technology and investigated an enzyme called methane monooxygenase, which catalyzes the selective oxidation of methane to methanol with molecular oxygen. His work at the University of Wisconsin has been recognized by several awards, including the NSF CAREER Award, the Dreyfus New Faculty Award, the Research Corporation Innovation Award, and the Dow Chemical Company Innovation Award.



Shannon Stahl

## The Unmaking and the Making of Chemical Elements: The Chemistry of Salts in the 18th Century

Thomas Broman  
Professor, Department of History of Science  
University of Wisconsin-Madison

In order to appreciate the importance of oxygen's discovery, we must understand that it involved far more than the isolation and identification of a single element. Especially for Lavoisier and his colleagues in France, oxygen was part of a much broader redefinition of chemical elements and the role played by those elements in chemical phenomena. During the 17th century, the work of "sceptical chymists" such as Robert Boyle and Rudolph Glauber had begun to undermine chemists' understanding of chemical phenomena in terms of the traditional Aristotelian scheme of four elements (air, earth, fire and water) or the more recent and chemically attuned Paracelsian trio of principles (mercury, sulfur and salt). Although such fundamental elements were still useful in many respects, Boyle and Glauber and their compatriots began to be interested in reactions such as the reversible process whereby nitre (potassium nitrate) could be decomposed into spirit of nitre (nitric acid) and salt of tartar (potassium carbonate). The reversibility of these reactions prompted chemists to begin thinking about chemical substance not in terms of fundamental elements, but more "operationally" in terms of non-elemental components that enter into combination with each other. Such thinking, however, was beset by severe conceptual difficulties. How was it possible for substances such as salt of tartar and spirit of nitre to combine and indeed persist in the product – a persistence demonstrated by the ability to obtain them again under different circumstances – and yet not display any of their characteristic properties? More fundamentally, chemists confronted the question of what it meant to say that certain parts of the cream of tartar and spirit of nitre "persisted" in what was most evidently a different substance.

In this talk, I will describe the efforts of 18th-century chemists to grapple with these issues and develop a comprehensive understanding of the rules of combination for different acids and bases in the production of what came to be called "middle salts." And, as I will show, the idea of acid-base reactions as involving the exchange of quasi-elemental units was decisive in Lavoisier's identification and naming of oxygen as an "acidifying principle."

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Tom Broman is Associate Professor of History of Science and History of Medicine at the University of Wisconsin-Madison. After obtaining a B.A. in chemistry and biology at Ripon College in 1976, he took an M.S. degree in agronomy at the University of Illinois at Urbana-Champaign and then a Ph.D. in history from Princeton University in 1987. He is the author of *The Transformation of German Academic Medicine, 1750 - 1820* (Cambridge, 1996), and, with Lynn Nyhart, he is the editor of *Science and Civil Society: Historical Perspectives* (Univ. of Chicago, 2002), a volume that examines how the interplay of beliefs concerning science and civil society has worked to legitimize the institutional forms of civil society and naturalize its ideologies, while at the same time giving to science its overwhelmingly powerful role in public life. He is currently writing a book on the periodical press and the formation of the public sphere in 18th-century Germany. Tom's teaching in Madison includes science in the Enlightenment and a survey course on ancient, medieval and early modern medicine. (Photo page 14.)

## Oxygen and the Aging Process

**Richard Weindruch**  
**Professor, Department of Medicine**  
**University of Wisconsin Medical School**

There has been a long-standing interest in the role that oxygen may play in the aging process. In 1908, it was suggested that species of mammals with higher metabolic rates (*i.e.*, rates of oxygen consumption) generally were short-lived – such as mice and rats which live only about 3 years. On the other hand, species of mammals with lower metabolic rates (such as elephants and humans) were long-lived. In 1928, studies in cold-blooded animals, such as frogs, in which metabolic rates can be changed by altering temperature of the surrounding environment, confirmed the suspected relationship between oxygen consumption and longevity. These findings formed the basis of the “rate of living” theory of aging.

More recently, the rate of living (or metabolic rate) theory has been linked to the body’s rate of production of partially reduced oxygen species (also known as oxygen free radicals), which are normal byproducts of the body’s use of oxygen to generate energy inside cells. Free radicals are highly reactive molecules with unpaired electrons that are prone to destructively oxidize compounds they encounter. Free radical production occurs in mitochondria, which are the tiny intracellular structures that serve as the power plants of cells and may be importantly involved in the aging process. For example, the rates of mitochondrial free radical production and levels of damaged molecules increase with age in several organs of laboratory mice and rats. Also, oxygen free radicals regulate many normal cellular functions as well as pathways of cellular death.

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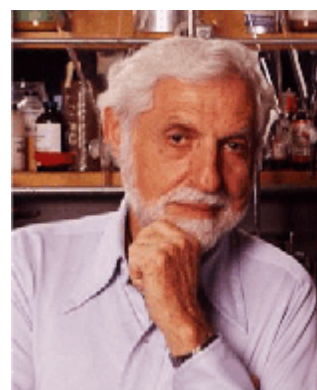
Richard Weindruch is a Professor of Medicine at the University of Wisconsin. For 27 years, he has studied caloric restriction, which is known to slow the aging process in experimental animals. He is the author of two books, 80 peer-reviewed research reports and 60 review articles. He has received several awards for his research including the Gerontological Society of America’s Kleemeir Award (1998), the Glenn Foundation Award (2000) and the National Institute on Aging’s Nathan Shock Award (2000). From 1994 to 1999 he served as Chairman of NIH’s Geriatrics and Rehabilitation Medicine Study Section.



Thomas Broman



Richard Weindruch



Carl Djerassi

## How to Smuggle Science to the Public

Carl Djerassi  
Professor, Department of Chemistry  
Stanford University  
(Co-author of the play *OXYGEN*)

The border between knowledge and belief is always fuzzy, but nowhere is it fuzzier than in the public's acceptance of science. Just because one believes something does not mean one knows it. Superstition is based on that truism. As is the reverse: not believing something, even though one knows it to be a fact. Lowering the barrier between knowledge and belief is one of the purposes of more effective communication between scientists and the lay public. And looking for new means of doing so is clearly desirable. My own initial attempts to accomplish that through the medium of fiction – through a tetralogy of “science-in-fiction” novels, where all the science is correct or at least plausible, in contrast to science fiction, where neither feature is required – have been sufficiently successful to prompt me to extend this “information smuggling” approach to the theatre. But can “science-in-theatre” also fulfill an effective pedagogic function on the stage or are pedagogy and drama antithetical?

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Carl Djerassi, professor of chemistry at Stanford University, is one of the few American scientists to have received both the National Medal of Science (for the first synthesis of a steroid oral contraceptive – “the Pill”) and the National Medal of Technology (for promoting new approaches to insect control). A member of the US National Academy of Sciences and the American Academy of Arts and Sciences and many foreign academies, Djerassi has received 19 honorary doctorates and many other honors, such as the first Wolf Prize in Chemistry, the first Award for the Industrial Application of Science from the National Academy of Sciences, and the American Chemical Society's highest award, the Priestley Medal. He received his PhD in chemistry (1945) from the University of Wisconsin-Madison.

For the past decade, he has turned to fiction writing, mostly in the genre of “science-in-fiction,” whereby he illustrates, in the guise of realistic fiction, the human side of scientists and the personal conflicts they face in their quest for scientific knowledge, personal recognition, and financial rewards. He has written 5 novels (*Cantor's Dilemma*, *The Bourbaki Gambit*, *Marx, deceased*, *Menachem's Seed*, and *NO*) as well as short stories (*The Futurist and Other Stories*), autobiography (*The Pill*, *Pygmy Chimps*, and *Degas' Horse*) and a memoir (*This Man's Pill*.) He recently wrote the word-play “NO,”<sup>†</sup> and also embarked on a trilogy of “science-in-theatre” plays. *An Immaculate Misconception*, was first performed at the 1998 Edinburgh Fringe Festival and subsequently in London, San Francisco, Vienna, and Cologne; Sweden; Sofia, Bulgaria; and Geneva, Switzerland. It was broadcast by BBC Radio in May 2000 as “Play of the Week” and in 2001 by both West German and Swedish Radio. *OXYGEN* (co-authored with Roald Hoffmann) premiered in 2001 at the San Diego Repertory Theatre and at the Riverside Studios in London. It was broadcast by BBC World Service and the West German Radio in December 2001. A radio play adaptation of *The Bourbaki Gambit*, was broadcast by West German Radio in June 2000. (For more about Djerassi's writing, go to [www.djerassi.com](http://www.djerassi.com).)

He also founded the Djerassi Resident Artists Program near Woodside, California, which has provided residencies and studio space for over 1100 artists in the visual arts, literature, choreography and performing arts, and music since 1982.

<sup>†</sup>*NO* had its American premiere reading March 28, 2003 before an audience of students and staff in instructor Rodney Schreiner's general chemistry class at the University of Wisconsin-Madison. Roles in this pedagogic word play about nitric oxide were read by Djerassi and by UW-Madison chemistry professors Laura Kiessling and Bassam Shakhshiri.

## Notes on the Demonstrations

A number of the following demonstrations are described in detail in the series *Chemical Demonstrations: A Handbook for Teachers of Chemistry, Volumes 1–4*, Bassam Z. Shakhashiri, University of Wisconsin Press. Volume and page numbers cited after the descriptions refer to this publication.

**#1A Generating Oxygen: Decomposition of Hydrogen Peroxide I** — Hydrogen peroxide is a naturally unstable combination of oxygen and water that willingly decomposes into its components. For example, when we put a dilute solution on our skin, the natural salts and acids of our skin cause  $\text{H}_2\text{O}_2$  to begin bubbling as the oxygen makes its escape. In this demonstration, we use a concentration of  $\text{H}_2\text{O}_2$  (about 30%) that is much more powerful than the medicinal variety, and we add a catalyst (manganese dioxide) to speed up the reaction. As oxygen and water are rapidly generated from the decomposing  $\text{H}_2\text{O}_2$ , so much heat is released that the water in the mixture boils. The released oxygen and water vapor shoot a spout of steam into the air. (Vol. 2, p. 137)

**#1B Generating Oxygen: Decomposition of Hydrogen Peroxide II** — So that we can better see what happened in the previous experiment, we have added a little detergent to the tall cylinder this time. As the bubbling oxygen gas is generated from the hydrogen peroxide, it gets caught up in detergent bubbles. Unable to rapidly escape, it creates a big fat cascading tube of foam, which some have called “elephant’s toothpaste.”

**#1C Impact of Pure Oxygen on Combustion** — Oxygen makes up only 21% of the air. When it is available in a higher concentration, it oxidizes or combines with other elements at a faster rate than normal. In this case, a tiny spoonful of sulfur, burning with a small blue flame in ambient air, is lowered into a flask containing pure oxygen. The flame immediately expands, burning bright blue and quickly oxidizing the sulfur to sulfur dioxide. (Vol. 2, p. 184)

**#2 Using Indicator Dyes to Monitor Oxidation** — “Indicator solutions” rely on dyes or indicator chemicals that dramatically change color – for example, from blue to clear or from blue to yellow – to indicate that chemical conditions have changed. Sometimes the change is caused by the addition of hydrogen ions to the dye; sometimes it is caused by the addition of oxygen or other elements. In this demonstration, methylene blue dye is mixed with dextrose, a sugar, and potassium hydroxide in a flask. The dye is an indicator but also a catalyst that helps dextrose pick up oxygen. If the flask sits quietly, the dextrose picks up dissolved oxygen while also contributing 2 hydrogen atoms to each dye molecule, causing the blue color to disappear. If the flask is then shaken and oxygen gas is mixed into the solution, the oxygen grabs the hydrogen away from the indicator dye and the blue color returns. If the flask sits again, methylene blue will again be reduced by dextrose and become colorless. After repeated shakings and sittings, all the available oxygen will be consumed by dextrose oxidation and the color changes will cease to occur. (Vol. 2, p. 142)

**# 3 Mozart Performance** — Profs. Marc Fink, David Perry, Richard Blum, and Parry Karp — See page 18 for background.

**#4A Oxidation of Copper** — Oxygen bonds with many metals. Two of the most familiar products of such union are rusty iron and weathered copper. This demonstration shows how these reactions are accelerated by heat and by increased concentration of oxygen. When a small “tent” of copper is heated over a Bunsen burner, it begins to react with ambient oxygen, becoming iridescent and then black, the color of copper oxide. But if the burner is turned off and the still-hot copper is bathed in a blast of hydrogen gas, the metal immediately becomes a fresh pink copper color: the oxygen in the hot copper oxide has left the copper and reacted with hydrogen to form water vapor. But as soon as the hydrogen

stream is removed, if the copper is still hot, it will immediately bond with the surrounding oxygen, instantly becoming black again.

**#4B Rapid Oxidation of Iron** — Heat and concentrated oxygen can also accelerate the rusting process in a dramatic way. In this case, a bit of steel wool held on the tip of a long wire is heated until it is red hot. When removed from the flame and dropped into a flask of pure oxygen, the steel wool bursts into flames with a shower of sparks, producing two or three forms of iron oxides. Significantly, when the experiment is finished the iron residues will weigh more than the original steel wool because they now also contain oxygen. Antoine Lavoisier, who was the first chemist to appreciate the importance of precise measurements in elucidating chemical reactions, picked up on these weight differences, leading him to important understandings of oxygen and oxidation.

**#5A Paramagnetism of Liquid Oxygen** — In most elements, the molecules contain an even number of electrons which spin in pairs. Oxygen is one of those rare elements that contain an even number of electrons but not all are in pairs. This means that oxygen responds to magnetism. But how do we show that? The easiest way is to surround a coil of oxygen with frigidly cold liquid nitrogen until oxygen condenses to form a beautiful blue liquid. When the liquid oxygen is poured between two poles of a magnet, it will hover between the poles instead of flowing away as a non-magnetic substance would do. Shortly, the oxygen evaporates into its gas form. (Vol. 2, p. 147)

**#5B Evidence of Singlet Oxygen** — As we mentioned above, molecular oxygen is unusual in that it normally contains an even number of electrons but not all are paired. Singlet oxygen, by contrast, is a molecule in which all the electrons are paired. It's an unstable state for oxygen and one which the gas is eager to leave, eager to return to normal molecular oxygen. Not surprisingly, singlet oxygen is short-lived and not very common. But when oxygen is produced rapidly in an intense reaction, singlet oxygen's presence can be detected amidst the molecular oxygen. The tell-tale is a dull red glow that is given off as the singlet "relaxes" to molecular form and releases energy as photons of light. This is called chemiluminescence. In our demonstration, the red glow can be seen in the frothy bubbles of oxygen suddenly produced when equal concentrations of hydrogen peroxide ( $H_2O_2$ ) and chlorine gas, or bleach ( $NaOCl$ ), are mixed. Sometimes sensitizers are added to enhance the glow. These are compounds that are also luminescent, but more so than singlet oxygen. When excited by energy released from singlet oxygen, the sensitizers may glow a bright red or green. (Vol. 1, p. 127)

**#6A Oximetry: Measuring Oxygen in a Breath** — There are various non-invasive ways to measure oxygen levels in the human body. One device measures how much oxygen our lungs are able to pick up by measuring how much oxygen is left in our breath when we exhale. (This device uses oxygen's magnetic characteristics to distinguish oxygen from carbon dioxide and the other gases present in a breath of air.) Oxygen makes up 21% of the ambient air that we inhale; the air that we exhale contains only about 15% oxygen.

**#6B Oximetry: Measuring Oxygen in the Body** — Another non-invasive device measures the amount of oxygen that our blood is actually carrying. It relies on a clip that slips over the end of a finger and that directs a small intense beam of red light through the finger. If the finger is well oxygenated and its blood is deeply red, the light beam passes through the finger and is picked up by a sensor in the clip. If blood is poorly oxygenated and is bluish, the red light beam is blocked by the blue and the sensor reflects that condition.

**#7 Thermite reaction** — This reaction is most notable for the amount of heat it produces and for the fact that, once it gets going, it provides its own oxygen supply and is self-sustaining. The key reactants are aluminum powder ( $Al$ ) and iron oxide powder ( $Fe_2O_3$ ). Aluminum does not react with iron oxide at ordinary temperatures. For the reaction to occur, the mixture must be heated to a high temperature. This



is done by inserting a burning sparkler into the mixture. When heated enough, the oxygen in iron oxide is transferred to the aluminum, the aluminum is oxidized, and iron oxide is reduced. Once this reaction begins, it generates plenty of heat to keep going. In fact, it produces so much heat that one of the products, iron, is produced in the molten state! Variations on this type of reaction have been developed into industrial processes for separating iron and other metals from their oxides, for welding metals, and for producing incendiary bombs with a chemical fuse. (Vol. 1, p. 85)

## The Music of Mozart

Wolfgang Amadeus Mozart, who was a younger contemporary of the scientists Antoine Lavoisier, Joseph Priestley, and Carl Wilhelm Scheele, is widely regarded as one of the greatest composers in the history of Western music. He wrote in all the musical genres of his day and excelled in every one. An exceptional prodigy, at the age of four he was playing the harpsichord and at five he was composing. Mozart's father described him as "the miracle which God let be born in Salzburg," and he believed it his duty to God to give notice of this miracle to the world, and incidentally, to profit from doing so. From childhood Mozart toured Europe, performing before the aristocracy and the public. At the age of 13, on his first Italian tour, Mozart heard the Sistine Choir perform the famous *Miserere* of Gregorio Allegri – music that was guarded as the choir's exclusive domain. However, afterwards Mozart wrote it out from memory. Mozart was a prodigiously productive composer. Among his works are over a dozen operas, 56 symphonies, 40 liturgical works, 35 concertos, 21 serenades, numerous violin and piano sonatas, 26 string quartets, several quintets and quartets for various instruments, including a quartet for oboe and strings. His works are notable for their clarity of form, economy of means, and range of expression. When he died in 1791 of a still unknown cause, he was only 35 years old. (The theory that he was poisoned by his rival, Salieri, as put forth in the popular play and motion picture *Amadeus*, has largely been discredited.) The piece that we are hearing today – Quartet for Oboe and Strings, K. 370, First Movement: Allegro – was composed by Mozart in 1781, just four years after the fictitious meeting of Lavoisier, Priestley, and Scheele that figures in the play *OXYGEN*.

Performing the quartet are Marc Fink, oboe; David Perry, violin; Richard Blum, viola; and Parry Karp, violoncello. Messrs. Fink, Perry, and Karp are all professors in the School of Music. Messrs. Perry and Karp are current members of the Pro Arte Quartet, and Mr. Blum is an emeritus member.

## Oxygen: Its Life and Times

Oxygen is the most abundant element in the Earth's crust, forming hundreds of thousands of compounds – gases, liquids and solids. Not surprisingly, it makes up about two-thirds of the human body, mainly as a constituent of water and organic molecules. By weight, it makes up nine-tenths of the water in rivers, lakes, and oceans. (Remember, oxygen is part of the water molecule as well as a dissolved gas in water.)

In its elemental form, oxygen is a colorless, odorless, tasteless gas upon which most plants and animals depend for respiration. At extremely cold temperatures (below  $-183^{\circ}\text{C}$  or  $-297^{\circ}\text{F}$ ) oxygen becomes a beautiful pale blue liquid; at  $-218^{\circ}\text{C}$  ( $-360^{\circ}\text{F}$ ) it becomes a solid. Oxygen most commonly occurs as a pair of bonded atoms ( $\text{O}_2$ ) called a diatomic molecule, or “molecular oxygen.” Diatomic oxygen is unusual in showing magnetic properties, particularly in its liquid and solid states (refer to Demonstration 5A on p. 17). When oxygen is not bound to another element it is sometimes called free oxygen.

At the very top of Earth's atmosphere and in our busiest cities, oxygen occurs as a toxic 3-atom molecule called triatomic oxygen or ozone. Its presence high in the atmosphere provides an important shield against harmful ultraviolet radiation. However, ozone's presence at ground level as a product of smog is very damaging to life and materials.

Oxygen has an atomic number of 8, meaning that its atoms contain 8 protons. The atoms of natural oxygen are a mixture of three isotopes ( $\text{O}^{16}$ ,  $\text{O}^{17}$ , and  $\text{O}^{18}$ ) with three corresponding variations in their neutron numbers: 8, 9, and 10. The  $\text{O}^{18}$  isotope is sometimes used as a “tracer” to reconstruct paleontological or archeological events since  $\text{O}^{18}$  is always present in a known proportion (8 parts to 10,000 parts ordinary  $\text{O}^{16}$ ) in water, air, rocks and other materials. From about 1900 until 1961,  $\text{O}^{16}$  was used as the standard for atomic weights.

Although nitrogen gas – also colorless and odorless – makes up the lion's share (78%) of Earth's atmospheric gases, it is oxygen's 21% of the atmosphere that makes all the difference to living things. Nearly all plants and animals require oxygen for respiration. Even fish and aquatic insects “breathe” diatomic oxygen dissolved in water.

Oxygen levels in the air around us, however, have not always been a standard 21%. They have fluctuated significantly over Earth's lifespan. Before blue-green bacteria or algae evolved, the atmosphere held only trace amounts of oxygen. But as the primitive plants used the sun's energy to split apart water molecules and carbon dioxide molecules in order to create sugar, they also generated  $\text{O}_2$  as a byproduct. Even then, for eons plant-generated oxygen mostly dissolved into the Earth's oceans and was absorbed by and bonded with the minerals of the Earth's crust. Today oxygen-bearing rocks and minerals make up 49% of the weight of the Earth's crust. These include quartz, feldspar, olivine and other igneous rocks that are the base material for most sedimentary and metamorphic rocks.

Only when these oceanic and mineral “sinks” for oxygen were satiated did  $\text{O}_2$  begin to accumulate in the atmosphere in sufficient quantity to support other life forms. Animal life evolved by using oxygen to turn “fuel” (proteins, carbohydrates and fats) into energy. The waste products, carbon dioxide gas and water, are respired into the atmosphere where the  $\text{CO}_2$  is subsequently used by plants for photosynthesis. The result is an exchange of gases, called the oxygen cycle, between plant and animal kingdoms – each kingdom benefiting from the waste gas of the other.

Oxygen is a very aggressive element and combines readily with nearly all other elements. Of its 8 electrons, two occur in the first or innermost shell and 6 in the second shell. Because the second shell is “complete” only when it holds 8 electrons, oxygen is always eager to bond with elements that can contribute 1 or 2 of those sought-after electrons. For example, a single oxygen atom is satisfied by bonding with two hydrogen atoms ( $\text{H}_2\text{O}$ ) to form water; or two oxygen atoms are satisfied by bonding with carbon and sharing its 4 outermost electrons –  $\text{CO}_2$ .

Oxygen's high affinity for iron allows the red blood cells, which are the carriers of the iron-bearing hemoglobin molecule in vertebrates, to grab up oxygen from lungs (or gills) and carry it to waiting cells.

On their return trip to the lungs, hemoglobin and blood plasma carry off the waste gas carbon dioxide (CO<sub>2</sub>). Significantly, the iron of hemoglobin bonds with CO (carbon monoxide) more aggressively and holds CO more tightly than oxygen, making CO a very deadly gas that is capable of displacing oxygen from the blood.

Though beneficial to living organisms in so many ways, oxygen also can be damaging. During respiration, oxygen produces free radicals, molecules containing one or more unpaired electrons. Free radicals are very reactive and can oxidize or bond with vital molecules such as DNA. If radicals alter too many molecules, cellular systems suffer. The body's defenses destroy most free radicals but some last long enough to cause damage and are believed to be a prime cause of aging. Consuming food containing lots of antioxidants – such as vegetables, fruits and vitamins – is considered one way to sweep up and counteract free radicals, but its effectiveness is uncertain.

Sometime around 1.8 billion years ago, free oxygen began to build up sufficiently in the atmosphere that combustion, better known as fire, became a more common event. When an intense heat source such as lightning (or, today, a match) is available to start a reaction between oxygen and compounds such as wood, the heat of the reaction sustains itself until the heat, the fuel, or the oxygen are gone – basically, until all the free oxygen has combined with all the available elements in the fuel. In its quest for electrons, oxygen attacks wood's carbon-hydrogen bonds, converting most of the wood to oxygen-bearing compounds. The end products are hot invisible CO<sub>2</sub> gas, H<sub>2</sub>O as steam, and partly combusted particles and residual minerals as smoke and ash.

Reactions of this sort, in which oxygen acquires electrons from other sources (and bonds with those elements or compounds) are called oxidation reactions. But oxygen is not the only element that takes electrons. Thus the term “oxidation” also has a generic meaning and does not necessarily involve oxygen. The reactant that loses electrons (or loses its oxygen) is said to be reduced. Oxygen's normal rate of reaction with another element can be dramatically accelerated with additional heat and a higher concentration of oxygen. For example, the slow process of rusting can be converted to a flashing, sparking combustion when the iron is heated and the oxygen level is increased. (Refer to Demonstrations 1C on p. 16, and 4A and 4B, pp. 16-17.)

Oxygen's presence as a distinct factor in atmospheric air was suspected when eighteenth century scientists concluded that only a portion of air actually supported combustion. Prior to this the source of combustion was considered to be a mysterious substance called “phlogiston.” Scientists debated whether phlogiston was actually a form of matter or a force like gravity or electricity. They believed that when substances burned or rusted, they gave off phlogiston (those with more phlogiston burned hotter.) It took the contributions of three early scientists – French chemist Antoine Lavoisier, Swedish chemist Carl Wilhelm Scheele, and English cleric Joseph Priestley – looking at different aspects of the question, to finally isolate oxygen. Priestley believed oxygen had no phlogiston of its own and therefore drew it out of other substances. He called oxygen “dephlogisticated air.” Lavoisier, however, between 1775 and 1777 showed that combustion was supported by a distinct gas which he called oxygen. He showed that heat accelerates the bonding of oxygen with other materials, as when wood burns. (Burning is simply rapid oxidation.) He also recognized that rust was the product of the chemical combination of oxygen and iron (See pp. 21-23 for more details on oxygen's discovery.)

The greatest users of commercial oxygen today are producers of steel. Oxygen is injected into blast furnaces to combine with carbon compounds in the steel and remove those impurities in the form of CO<sub>2</sub> gas. Oxygen is also an important gas for welding and for the generation of other substances such as nitrate fertilizers and methanol.

## Oxygen's 18th Century Men of Discovery

### Joseph Priestley 1733-1804

Joseph Priestley was a political and religious revolutionary. But he was also a scientific conservative who clung to a disproved chemical theory.

Born in Yorkshire, England, Priestley was the son of a Nonconformist preacher (dissenting from the doctrine of the Church of England) and became a Unitarian minister. He was also a political rebel, supporting the American Revolution and later sympathizing with the French Revolution.

In 1766 Priestley met Benjamin Franklin in London. Franklin got Priestley interested in science and he was soon experimenting with electricity. Priestley was the first to suggest that electricity is important to chemistry. Priestley then took a pastorate in Leeds where he lived next to a brewery and became interested in the gases produced by fermentation. Priestley discovered the properties of carbon dioxide, including the fact that it produces a refreshing drink when dissolved in water. The Royal Society awarded him a medal for the discovery, and Priestley could be considered the father of the modern soft drink industry. Priestley also coined the name “rubber” after noting that the substance rubbed pencil marks off paper.



Joseph Priestley

Priestley continued to experiment with gases and isolated several, including oxygen, which he called “dephlogisticated air.” This refers to the theory of phlogiston, the idea that an invisible substance called phlogiston caused burning when it left a substance. Priestley believed that because his “dephlogisticated air” had little phlogiston, it removed it from other substances, causing intense burning. Even though Antoine Lavoisier disproved the phlogiston theory, Priestley continued to believe it until his death. Nevertheless, Priestley usually gets the credit for discovering oxygen. Though oxygen was first isolated by Wilhelm Scheele in 1771, three years earlier, Priestley published his results first.

In 1780 Priestley moved to Birmingham where he joined a renowned scientific society that included James Watt, credited with inventing the steam engine, and Erasmus Darwin, grandfather of Charles Darwin.

As the French Revolution turned violent, Priestley's well-known sympathy with it became dangerous. In 1791 an angry Birmingham mob burned his house along with most of his papers and equipment. Priestley and his family escaped to London and in 1794 emigrated to the United States with the help of Franklin. In the U.S., Priestley established friendships with others who were interested in science, including Thomas Jefferson. Priestley turned down offers of a Unitarian ministry and a university professorship and spent the last ten years of his life quietly writing, mostly in support of Unitarianism.

### The Phlogiston Theory

At the time of the discovery of oxygen, it was accepted theory that fire was a mysterious substance or force called phlogiston (flow-GIS-ton). Substances that burned well were thought to have a lot of phlogiston and fire was believed to result from phlogiston leaving the burning material. Antoine Lavoisier disproved the theory when he proved that the total products of burning are heavier than the

original substance. Lavoisier correctly deduced that burning is caused by a gas in the air combining with the burning material. He named the gas “oxygen.” He took the name from a Greek word for acid-forming, believing that all acids contain oxygen. He was wrong about that, but was the first to correctly explain fire, as well as rotting, tarnishing and rusting – reactions we now call “oxidation.”

### **Carl Wilhelm Scheele** **1742-1786**

Carl Wilhelm Scheele (SHAY-leh) was the first to isolate oxygen and study its properties, but he did not get credit for its discovery.

Scheele was born to a poor family in German-speaking Pomerania, which was then ruled by Sweden. At the age of 14 he was apprenticed to an apothecary. Apothecaries made their own drugs and were the most advanced practical chemists of their day. Scheele’s curiosity and tireless experimenting made him one of the best apothecaries in Europe and he soon found work in Sweden. He was offered positions at universities and royal courts but turned them down, preferring to continue working as an apothecary while conducting experiments on his own.



Carl Wilhelm Scheele

Scheele first isolated oxygen (which he called “fire air”) in 1771. But his book describing his experiments was not published until 1777 due to his publisher’s negligence. Meanwhile, Joseph Priestley reported his own experiments and usually gets credit for discovering oxygen. Scheele also isolated several other elements but does not get undisputed credit for discovering any of them. Scheele does get credit for discovering several acids and some poisonous gases. He kept meticulous notes on all the properties of his discoveries. He even recorded the taste of hydrogen cyanide, though exposure to the gas is usually fatal. Scheele died at 43 and his death may have been hastened by his habit of tasting new compounds. His symptoms resembled mercury poisoning.

Like Priestley, Scheele did not realize the implications of the discovery of oxygen. Both clung to the phlogiston theory (see Priestley biography). It was Antoine Lavoisier who first realized that burning occurs when oxygen combines with other substances.

## Antoine Laurent Lavoisier 1743-1794

Antoine Lavoisier's great ambition was to be credited with the discovery of an element. He failed to do that, but because of his interpretation of contemporary discoveries, he deserves to be called the father of modern chemistry.

Lavoisier (la-vwah-ZYAY) was born to a wealthy family in Paris and got an excellent education. He developed an interest in science at an early age and conducted experiments throughout his life. In 1771, Lavoisier married Marie-Anne Paulze, the daughter of another wealthy family who was only 13 at the time. She enthusiastically participated in his work, taking notes, making translations and illustrating his books.

From the beginning of his experimentation, Lavoisier insisted on extremely accurate measurements, his first contribution to modern chemistry. This allowed him to accurately interpret what happened in his experiments. For example, he burned phosphorus and sulfur and proved that the total products weighed more than the original substance. That meant that the substances must be combining with something in the air, which he named "oxygen." Lavoisier's experiments disproved the popular phlogiston theory (For an explanation of this theory, see the accompanying Priestley biography). Later he showed that combustion and human metabolism are fundamentally the same – both consume oxygen and materials containing carbon and hydrogen to produce carbon dioxide and water. Lavoisier's meticulous measurements also led him to recognize the concept of conservation of matter – that chemical reactions, including burning, do not destroy matter but merely change it.



Antoine Lavoisier

In collaboration with other chemists, Lavoisier published a book called *Methods of Chemical Nomenclature*, establishing a consistent system for naming chemicals which still forms the basis for naming chemicals today. Previously, alchemists and chemists had used their own terminology, some of it fanciful or purposely obscure, so chemists often didn't know what other chemists were talking about. In 1789 Lavoisier published his *Elementary Treatise on Chemistry*, the first modern chemical textbook, another reason to consider him the father of modern chemistry.

In 1794, Lavoisier was beheaded during the Reign of Terror following the French Revolution, even though he had supported the revolution from the start. He was part owner of a tax collecting company, which made him a target. The king had used private tax collectors who made money by collecting a commission for themselves. Lavoisier's father-in-law also ran a tax collecting company, and also went to the guillotine. In addition, Lavoisier had made an enemy of one of the leaders of the Reign of Terror, Jean-Paul Marat, who fancied himself a scientist. Years before, Marat had submitted papers to the French Academy of Sciences, which Lavoisier correctly dismissed as worthless.

Within a few years of his death, Lavoisier's tremendous contributions to science were recognized, and he became a national hero.

## A Glossary of Oxygen-related Terms

**Acid** Acids are substances that share a common set of properties including the ability to change the color of certain vegetable dyes, to form carbon dioxide gas when combined with a carbonate rock such as limestone, and to release hydrogen gas when in contact with certain metals such as iron and zinc. Acids have a sour taste, and their name comes from the Latin word for sour, *acidus*. All acids contain hydrogen. When dissolved in water, acids release ionized hydrogen atoms which react strongly with many substances, especially bases (see “Base”). Antoine Lavoisier coined the name “oxygen” from Greek words meaning “acid forming”. Oxygen is in some acids; for example, burning sulfur produces sulfur dioxide (SO<sub>2</sub>), and this, when mixed with water, produces sulfurous acid (H<sub>2</sub>SO<sub>3</sub>), a component of acid rain. But Lavoisier was only partially correct – some acids, such as muriatic acid (hydrochloric acid, HCl) contain no oxygen at all. Acids vary in strength. Some are highly corrosive and others, such as vinegar (ethanoic acid) and vitamin C (ascorbic acid), are relatively weak.

**Aerobic** Requiring oxygen. Especially applied to organisms that need oxygen to live. Also, describes exercise during which the body takes in more oxygen than it uses.

**Allotropes** Different forms of the same element that exist under the same temperature and pressure conditions. Oxygen exists in the atmosphere as both O<sub>2</sub> (two atoms forming a molecule) and an allotrope called ozone, O<sub>3</sub> (three atoms per molecule).

**Anaerobic** Not requiring oxygen. Applied to organisms that don’t need oxygen to live. For some of them, oxygen is toxic. Also describes exercise during which the body uses more oxygen than it takes in, drawing from reserves.

**Antioxidant** A substance that inhibits the oxidation of another material. The antioxidant may do this by reacting with oxygen itself, or by inhibiting the formation of free radicals of oxygen. Vitamins C and E are antioxidants. (See also “Free Radicals.”)

**Aristotelian chemistry** Aristotle (384-322 BCE) believed the elements were earth, air, fire, and water, the prevailing “chemistry” of the time. Aristotle rejected the concept of atoms developed by Democritus.

**ATP** Adenosine triphosphate, the compound used by cells to store energy in chemical form.

**Atom** The smallest particle of an element that retains the chemical properties of the element.

**Base** Also called alkali. Bases are substances with a common set of properties including a soapy feel, a bitter taste, and the ability to reverse the color change in vegetable dyes caused by acids. When mixed with water, bases release negatively charged hydroxide ions (HO<sup>-</sup>) which react strongly with the positively ionized hydrogen ions in acids to form water, thereby neutralizing acids. Antacids such as bicarbonate of soda (NaHCO<sub>3</sub>) neutralize stomach acid (hydrochloric acid, HCl). Another base, lime (calcium oxide), is used to neutralize over-acidic soil.

**Caloric restriction** Limiting food intake to the bare minimum needed for survival. This has been shown to extend life spans in laboratory mice and rats, perhaps by limiting the action of free radicals. (See also “Free Radicals.”)

**Carbohydrate** A compound of carbon that also contains hydrogen and oxygen in the same ratio that they have in water, two hydrogen atoms per oxygen atom. The general formula for a carbohydrate is  $C_x(H_2O)_y$ , where x and y are whole numbers.

**Catalyst** A substance that speeds up a chemical reaction, but which is unchanged when the reaction is complete.

**Chemiluminescence** The emission of light as a result of a chemical reaction at ambient temperatures, not as a result of heat. Also referred to as “cool light.”

**Combustion** The reaction of a compound with molecular oxygen to form products in which all the elements are combined with oxygen. For example, the combustion of natural gas, which is mostly methane ( $CH_4$  - carbon and hydrogen), produces carbon dioxide ( $CO_2$ ) and water ( $H_2O$ ).

**Dephlogisticated air** Joseph Priestley’s name for oxygen. (See “Phlogiston.”)

**Diatomic** Made up of two atoms. Atmospheric oxygen,  $O_2$ , is diatomic.

**Electron** A negatively-charged subatomic particle. Electrons occupy the space on the periphery of atoms, and they are involved in chemical reactions.

**Electron transport system** The process by which electrons are transferred from one molecule to another during a chemical reaction. During the chemical reactions involved in animal metabolism, the process of changing oxygen and carbohydrates into carbon dioxide and water proceeds through several stages, each stage involving the transfer of electrons from one substance to another.

**Endothermic process** One that requires energy, usually drawing heat from the surroundings. Breaking chemical bonds requires energy and is endothermic.

**Enzyme** A catalyst produced by a living organism that speeds up chemical reactions. Enzymes allow the body to oxidize carbon compounds and produce energy.

**Exothermic process** One that releases energy in the form of heat. The formation of chemical bonds releases heat. For example, heat released by burning natural gas (methane,  $CH_4$ ) results from the formation of chemical bonds between oxygen and the carbon and hydrogen in methane.

**Explosion** Rapid combustion reaction that forms large volumes of gas from solid or liquid reactants. The sudden increase in volume causes shock waves in the air. (See also “Combustion.”)

**Flame** The zone of burning gases and particulate matter associated with rapid combustion. Hot particles emit the light characteristic of fire.

**Free radicals** Molecules that contain one or more unpaired electrons. Free radicals are very reactive, and seldom persist for very long. In organisms, free radicals are produced continuously at low levels during respiration. They can oxidize and damage vital components of cells and tissues. The body has defenses that destroy most free radicals, but some radicals last long enough to cause damage. The gradual accumulation of cellular damage is one of the causes of aging. Much of the damage from nuclear radiation is caused by the creation of free radicals from water inside the body. Cigarette smoke is a major source of free radicals; a single puff of cigarette smoke may contain a million billion ( $10^{15}$ ) free radicals.



**Glucose** A type of simple sugar, converted by living cells to the carbohydrate glycogen. Glucose is the cell's source of energy and is also used in building fats and proteins. Diabetes results from poor control of blood glucose by the hormone insulin.

**Green chemistry** Chemical manufacturing processes that do not produce harmful by-products.

**Half-life** Time required for the concentration of a reactant to reach half its initial value. Also the time required for an unstable (or radioactive) isotope to lose half its radioactivity (see "Isotope").

**Hemoglobin** The iron-containing protein in red blood cells that carries oxygen. Iron atoms in hemoglobin bind with oxygen molecules in the lungs and release them in the tissues of the body. Oxygenated hemoglobin, oxygen-rich after leaving the lungs, is carried in the arteries and is brighter red than the dark deoxygenated hemoglobin, which has given up its oxygen and is returning to the lungs via the veins. This is why veins look bluish and are more visible under the skin than arteries.

**Hydrogen peroxide** A compound of oxygen and hydrogen, whose molecules each contain two atoms of oxygen and two atoms of hydrogen. In this compound,  $H_2O_2$ , the bond between the two oxygen atoms is relatively weak, making hydrogen peroxide quite reactive. Though hydrogen peroxide is a toxic by-product of animal metabolism, the liver contains an enzyme which quickly breaks down hydrogen peroxide into water and oxygen. Some free radicals may be released in the process.

**Isotopes** Two or more forms of an element whose atoms have the same atomic number (number of electrons and protons), but have different atomic weights because they have different numbers of neutrons. The ratio of isotopes in a substance can reveal how and when the substance was formed. For example, the isotopes carbon-12 (6 protons and 6 neutrons per atom) and carbon-13 (6 protons and 7 neutrons) in coal may reveal the oxygen content of the atmosphere at the time coal beds were formed. And the concentration of carbon-14 in organic matter can be used as a reliable dating system because carbon-14 (6 protons and 8 neutrons) is known to decay at a steady rate, with a half life of 5570 years.

**Metabolism** The chemical and physical processes for maintaining life. In aerobic organisms, producing energy by the oxidation of carbohydrates.

**Middle salt** A substance formed by the reaction of an acid and a base. For example, hydrochloric acid, HCl, and sodium hydroxide, NaOH, form sodium chloride, NaCl (table salt) and water,  $H_2O$ . Observations of the reversibility of certain reactions of acids and bases and their middle salts led early chemists to the idea that an element might be composed of smaller particles (today's electrons and ions) that could interact with another element without changing the basic nature of either element.

**Mitochondria** Structures within cells that are the center of energy production, making the cell's ATP (see "ATP").

**Molecular oxygen** The form of elemental oxygen which contains oxygen molecules. The free oxygen in the atmosphere is molecular oxygen in which each molecule contains two atoms of oxygen,  $O_2$ .

**Molecule** The smallest stable structural unit of an element or compound that displays its characteristic physical and chemical properties. Oxygen can't persist as single atoms and is commonly found as a molecule containing two atoms,  $O_2$ , or three atoms,  $O_3$  (ozone), or in compounds with other elements.

**Osmosis** The transfer of water or solvent molecules through a membrane from a region of higher solution concentration to a region of lower concentration.

**Oxidant** A substance, also called the oxidizing agent, that provides the oxygen for a chemical reaction (or that causes the oxidation of another substance by removing electrons from it.) For example, in gunpowder the oxygen for rapid combustion is provided by the oxidant potassium nitrate ( $\text{KNO}_3$ ), also known as saltpeter.

**Oxidase** An enzyme that promotes oxidation. Oxidases are metabolic catalysts that assist in the transfer of electrons from glucose to oxygen, producing water and releasing energy. This is the final step in aerobic respiration, the opposite of the water-splitting reaction of photosynthesis.

**Oxidation** A chemical process in which electrons are transferred from one substance to another. The substance that loses electrons undergoes oxidation. Oxidation often involves oxygen, but not always; the term also refers to any chemical reaction in which electrons are transferred. The opposite of oxidation is reduction, the gain of electrons. The substance that gains electrons is the oxidizing agent. Oxidation and reduction always occur simultaneously.

**Oxygen metabolism** The biochemical processing of oxygen to produce energy. The rate of oxygen use.

**Oxygen tension** The level of oxygen in mixed gases. The atmosphere contains 21% oxygen.

**Oxygenase** An enzyme that serves as a catalyst for reactions in which oxygen atoms are incorporated into new molecules.

**Ozone** An allotrope of oxygen whose molecules each contain three oxygen atoms ( $\text{O}_3$ ). Ozone can be formed by electrical discharge, ultraviolet rays, and within internal combustion engines. In the upper atmosphere, ozone helps screen out harmful ultraviolet radiation. However, ozone is toxic and in air at surface level is considered a pollutant. Ozone has a bluish color and a strong odor.

**Paracelsian chemistry** Named for German physician and alchemist Paracelsus (1493-1547) who objected to the Aristotelian chemistry of earth, air, fire and water and instead proposed a chemistry based on three principles: sulfur, salt and mercury. These were seen as sources of energy, not elements in the modern sense, and he considered them analogous to the Holy Trinity. Paracelsus believed the goal of alchemy should be to find new medicines, not to make gold. Paracelsus emphasized experimentation and favored far more openness at a time when alchemists jealously hid their secrets. Paracelsus took his name from the Latin meaning “better than Celsus”, an ancient Roman physician whose works had recently been rediscovered. His birth name was Theophrastus Bombastus von Hohenheim.

**Paramagnetic** The physical property of being attracted to a magnetic field. Paramagnetism is caused by the presence of unpaired electrons in a substance.

**Phlogiston** (flow-GIS-ton) A hypothetical substance or force believed by early scientists to cause combustion by leaving the burning material. Joseph Priestley believed oxygen had no phlogiston and drew it out of other substances, intensifying combustion.

**Photosynthesis** The chemical process in which green plants (and blue-green bacteria ) utilize the energy of sunlight or other light to convert carbon dioxide and water into carbohydrates, with the green pigment chlorophyll acting as the energy converter. The process releases oxygen and is the chief source of atmospheric oxygen.

**Reduction** The opposite of oxidation. (See “Oxidation.”)

**Saturated fat** A fatty acid molecule whose carbon chain is fully saturated with hydrogen atoms and contains no double bonds between carbon atoms. (See “Unsaturated fat.”)

**Superoxide** An ion composed of a diatomic oxygen molecule with a single negative charge. Superoxide ions have an odd number of electrons, so all superoxide compounds are paramagnetic.

**Unsaturated fat** Fatty acid molecules that contain double bonds between carbon atoms (which means the carbon atoms are not saturated with their maximum number of bonds with hydrogen atoms). Unsaturated fats in the walls of mitochondria keep them more elastic than saturated fats, but the double bonds are more easily oxidized, creating free radicals. Animals with long life spans have lower levels of unsaturated fatty acids in their cells than short-lived animals, but the level increases with age.

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