An Introduction to Chemistry

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By

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PREFACE

Every year, enormous numbers of college students take courses having titles like "General Chemistry" or "Introductory Chemistry" either because entry level chemistry is a prerequisite for other courses that interest them, or because medical schools require it for admission, or both. That said, the real reason students should do so is the relevance of the material presented in these courses to their understanding of the world they live in. Life is a chemical phenomenon, as is much of geology. In addition, industries that depend on chemical technologies generate a large fraction of the gross domestic products of all advanced nations, and there is an unending need for new substances that have useful mechanical, physical, or biological properties, and for less disruptive technologies for generating energy and making the materials on which our way of life depends. A sound understanding of the principles of chemistry is essential for anyone considering a career that touches on any of these areas, and even those who are not so inclined could benefit.

A large fraction of the students who enroll in chemistry courses in college took a year (or more) of chemistry in high school. Consequently, some of them enter college ready for courses like organic or physical chemistry, which are the courses they should take if they wish to carry on. The preparations of the other members of this group vary a lot. A one-term refresher course may be enough to bring some of them up to speed, but most are unlikely to thrive in advanced courses until they have taken a full year of introductory chemistry at the college level, which is what chemistry departments usually require them to do. Not surprisingly, many of these students are unenthusiastic about repeating in college a course they feel they took in high school.

Over my career, I taught introductory chemistry to thousands of college students who had taken it before, and I knew how they felt about it because I had had the same experience in my own freshman year. Consequently, my goal was to find a way to reacquaint them with the basics of chemistry that would minimize their sense of *déjà vu*. They are the audience for whom this book is intended.

What distinguishes this textbook from other entry-level texts is its emphasis on the history of the science of chemistry. I have long believed that students who are shown how a scientific discipline came to be are likely to emerge not only with a deeper understanding of the subject than they would have otherwise, but also with a better sense of how science advances. In addition, and almost as important here, the historical focus of this text gives it a story line.

Finally, it has become fashionable in recent years to invert courses, i.e. to have students read at home the material that is presented in lecture in traditional courses, and to use the class time thus liberated for answering questions, and teaching students how to solve problems. This *modus operandi* is unlikely to succeed unless the textbook students are asked to read is readable, which not an adjective most would lightly apply to the average general chemistry textbook. Who would willingly read a thousand-page book that is so filled with worked problems, side boxes, bullet points, problem sets, diagrams, pictures, etc. that on many pages it can be a challenge to find the text? A shorter, simpler text that has a story line might work better.

NOTES FOR THE READER

Like Gaul, this book is divided into three parts. The first part, which is entitled Matter, starts with a discussion of how the science of chemistry began. It then describes how chemists came to realize that matter is made of atoms, and finally arrived at a full understanding of what atoms are, and how they combine to form molecules. It took roughly three centuries for this to happen, and the way chemists think about atoms and molecules today is shaped by the history of how it happened. Chemists still use concepts and vocabulary that were introduced into the field before chemical phenomena were fully understood. Thus, some knowledge of the history of the subject is required to understand not only what these ancient words and concepts mean, but also why they are still useful.

Some chemical reactions produce heat while others absorb it, and the heat evolved by some of those that do is routinely transformed into other kinds of energy. The second part of this book, Energy, deals with thermodynamics, which is the science of heat and energy. Its chemical implications are profound. Thermodynamics emerged as an identifiable branch of the physical sciences in the mid 19th century, and by the end of that century, it was fully formed. In this case, there is no corpus of archaic ideas and vocabulary that needs to be put into historical context, and so the reason for taking an historical approach to this aspect of chemistry is simply to give the narrative a story line.

In Part III of this book, Selected Topics, the concepts developed in its first two parts are used to illuminate three of chemistry's most important subdisciplines (organic chemistry, biochemistry, and nuclear chemistry), and to explore several topics relevant to everyday life in which chemistry is important.

The author assumes that his readers have had some prior exposure to chemistry, and for that reason, has not taken care to explain every important chemical word or concept the first time it appears in the text. That said, bold face type is used for each key word or concept at the point in the text where its meaning is explained. The reader will also note that whenever extended parenthetical comments of one kind or another seem appropriate, they are inserted into the body of the text in italics rather than being consigned to the footnotes.

As is usual for textbooks, this book is almost devoid of references, but the reader interested in exploring some of the topics it explores in greater depth might find the following books and articles interesting.

Part 1: Matter:

Brock, William H. 1993. *The Norton History of Chemistry*. New York: W.W. Norton & Co.

Emsley, John. 1989. *The Elements*. Oxford: Oxford University Press.

Lavoisier, Antoine-Laurent. 1789. *Traité Élémentaire de Chimie*. Paris: Cuchet. (A facsimile of Robert Kerr's English translation of this classic (Edinburg: Creech, 1790) can be obtained from Dover Publications.)

Scerri, Eric R. 2007. *The Periodic Table*. New York: Oxford University Press.

Part II: Energy:

Cardwell, Donald S. L. 1971. *From Watt to Clausius. The Rise of Thermodynamics in the Early Industrial Age*. Ithaca, NY: Cornell University Press.

Carnot, Sadi. *Reflections on the Motive Power of Fire*. (Eng. trans, Thurston, Robert H. 1960. New York: Dover Publications.)

Denbigh, Kenneth. 1981. *The Principles of Chemical Equilibrium*. Cambridge: Cambridge University Press.

Part III: Special Topics:

The issue of Chemical Reviews entitled "Batteries and Fuel Cells" (*Chemical Reviews*. 2004. 104 (10)).

Crabtree, George W., Dresselhaus, Mildred S. and Buchanan, Michelle V. 2004. "The Hydrogen Economy". *Physics Today* 57 (12): 39-44.

Higgins, Raymond A. 1993. *Engineering Metallurgy Part 1: Applied Physical Metallurgy*, 6th edition. London: Arnold.

ACKNOWLEDGMENTS

It is impossible for anyone who has taught general chemistry to have a view of the subject that is independent of those of the authors of the textbooks he or she employed in those courses. Of the many textbooks I used in the introductory chemistry courses I taught, the one I liked the best, and that influenced me the most was *Chemical Principles*, by Richard Dickerson, Harry Gray, and Gilbert Haight. It went through several editions, and although pdfs of this classic are still available on-line, it has been out of print for a long time. I gratefully acknowledge the intellectual debt I owe to its authors.

I also want to express my gratitude to my general chemistry students. They were the unwitting subjects of my pedagogical experiments, and I hope that whatever else I might have done to them, at least I did them no harm.

I am particularly grateful to Dr. Jonathan Parr for reading my manuscript at several stages of its development, suggesting ways that it could be improved, and encouraging me to carry on. I also want to thank my colleagues Professors Patrick Loria and J. Michael McBride for their comments about the manuscript. It should hardly need to be said that I am responsible for all of its remaining errors.

The reader will doubtless notice that the illustrations in this book do not have the finished, professional quality characteristic of those found in other textbooks. The reason is simple. I made most of them. The programs I used were ChemDraw® (PerkinElmer Informatics), Microsoft Excel®, Adobe Illustrator®, and MATLAB® (MathWorks).

Peter B. Moore
New Haven

PART I:

MATTER

CHAPTER ONE

ORIGINS: FROM BOYLE TO LAVOISIER

What is chemistry?

Chemistry is a natural science, which is to say one of the several academic disciplines that deals with everything in the universe that is not specifically human. This is not to say that the natural sciences have nothing to offer the humanist. For example, by providing accurate estimates of the ages of human artifacts, natural scientists have contributed significantly to the work of historians and archeologists. Nevertheless, the natural sciences have nothing much to add when it comes to literature, the arts, or most aspects of human history, for example. Indeed, natural scientists tend to treat *Homo sapiens* as a component of the natural world, like stars, rocks, elephants, and trees. So, while it would make sense for a scientist to study human evolution, or the impact of human activities on ecology, or the structure and function of the mammalian brain, it would probably be best for everyone if he or she were to leave literature and theology entirely alone.

The disciplines that make up the natural sciences can be divided into two classes: those that are historical, and those that are not. For subjects like cosmology, geology, and biology, history is of paramount importance. The goal of much of the activity in these disciplines is to reconstruct the history of the cosmos, the Earth, and the life forms that have inhabited it, respectively. For the mathematician, physicist or chemist, on the other hand, history does not matter. The logical structures mathematicians explore are timeless, and both physics and chemistry deal with properties of the universe that we have every reason to believe are the same today as they ever have been, or ever will be. Thus, in principle, all the open questions in physics and chemistry could be answered this afternoon if the right experiments were done. Moreover, there is no reason to think that the outcomes of those experiments would be any different if they were done by other people, at other times, or in other places. The assumption that the conclusions reached by physicists and chemists are independent of time and place is fundamental to the way geologists, biologists and cosmologists use them. Chemistry, the discipline of concern here, deals not only with the microscopic and macroscopic properties of substances, which are intimately related, of course, but also, and above all, with their reactions. Suffice it to say for the moment that a chemical reaction is a process that transforms one kind of substance into another.

While it is as certain as it can be that the laws of chemistry are universally valid, it is important to recognize that chemical phenomena determine outcomes in only a tiny part of the universe. The reason is that temperature controls the behavior of matter, and the number of places in the universe where the temperature is conducive to chemistry, i.e. to chemical reactions, is small. Much of the matter in the Universe is found in stars like the Sun. The temperature of the visible surface of the Sun is ~5800° C, and the temperatures in its interior are vastly higher. At those temperatures, there are no molecules, and consequently little happens that is of immediate interest to most chemists. Interstellar space, on the other hand, has very little in it at all; it is a high vacuum. Furthermore, most of the matter found there is very cold. Chemical reactions do occur in interstellar space, but they are very slow both because it is so cold, and because the concentrations of materials are so low. The surface of Earth, like the Little Bear's porridge, is not too hot, and not too cold, but just right. Thus, chemistry is an Earth-oriented science in the sense that the phenomena it deals with are extremely important on this planet's surface. In fact, the living organisms found on Earth are the most complex manifestations of the workings of the laws of chemistry known to exist in nature. No doubt there are other planets associated with other stars where surface temperatures are similarly conducive to chemistry. It is reasonable to think that life of some sort might exist, or might once have existed wherever this is, or once was true, but it is yet to be shown.

Humans have been doing chemistry forever

The science of chemistry did not begin to emerge in its modern form until the second half of the 17th century, but it would be a mistake to think that the pioneers of that era conjured it into existence out of thin air. The first reaction our ancestors learned to exploit is likely to have been the one that might be summarized as follows:

$$\text{wood} + \text{air} \rightarrow CO_2 \text{ (carbon dioxide)} + H_2O \text{ (water)} + \text{smoke} + \text{ash}$$
$$(+ \text{heat} + \text{light}), \text{ i.e. fire.}$$

As everyone knows, fires occur naturally because of lightning and volcanism; they are part of the natural environment. We do not know how, when, or where our ancestors first learned to control fire well enough to use it to cook, to keep warm, and to provide light at night. It probably happened tens of thousands of years ago, and probably more than once. Our ancestors were also acquainted with a reaction that can be summarized as follows:

$$CO_2 + H_2O + \text{minerals} + \text{light} \rightarrow \text{tree}.$$

This transformation is so complicated chemically, and in every other way, that if it was not so familiar we might still think it magic.

By ~1650, our ancestors had mastered an enormous amount of practical chemistry. For example, the ancients knew how to prepare iron, copper, lead, silver, tin, and mercury from their respective ores. They knew how to alloy copper with tin to make bronze, and they also knew how to convert iron into steel. Very early on, people learned how to make pottery, and ceramics. Glass appears to have been manufactured first in the Middle East about 3500 BC, but it was probably invented independently in China. The ancients knew how to make dyes to color themselves, and the fabrics they wove, as well as to paint the walls of their homes, and decorate their ceramics. They also had learned to cook, which is a delicate kind of biochemistry, and to make bread, beer and wine. About the time of the birth of Christ, some genius figured out how to make soap out of animal fat, a life-enhancing development we should all remember with gratitude. By the late middle ages, people also knew about distillation, which they used to extract alcohol from wine, and perfumes from plant material. In short, much of the chemistry still in everyday use was invented/discovered before 1650. The large number of substances that had been identified along the way, and the large number of reactions that had been discovered gave seventeenth century chemists a rich body of factual knowledge to work with.

It would also be a mistake to think that humans did not devise chemical theories prior to 1650. The written record extends back into ancient times in the Mediterranean basin, India, and China. Indeed, even in ancient times, people engaged in activities that looked a lot like modern chemical research. They worked on chemical reactions in special rooms that contained special equipment—laboratories in all but name. This activity, which we call **alchemy**, was pursued all over the ancient world, but following the fall of the Roman Empire, it ceased in Western Europe. Its revival in Western Europe, which occurred during the Middle Ages, was stimulated by interactions between Europeans and Islamic scholars, who had preserved and extended the Mediterranean tradition. The Islamic connection is plainly evident in words we still use like “alchemy”, “alembic”, and “alcohol”. In Arabic, the prefix "al" means "the".

Historians of science who devote themselves to the study of alchemy have been unkindly characterized as "tinctured with the kind of lunacy they set out to describe". Suffice it to say that alchemy was not as irrational as this uncharitable comment might lead you to believe. The things alchemists did in their laboratories were consistent with prevailing theories about the natural world, and while alchemists did strive to produce substances their sponsors craved, like the Elixir of Life, which would make those who drank it immortal, and the Philosopher's Stone, which was the reagent that would transform lead into gold, that was not all they had in mind. The work they did expanded our knowledge of substances and their reactions. Sulfuric, nitric and hydrochloric acids appear to have been prepared for the first time by medieval alchemists, for example, and alchemical texts from the late middle ages describe equipment and experimental procedures that continued to be used in chemistry laboratories well into the 19th century.

By the 17th century, the alchemical tradition had exhausted itself, and in retrospect, it is amazing it persisted as long as it did. Even though alchemists failed for centuries to produce either the Elixir of Life or the Philosopher's Stone—we are still waiting—somehow, they managed to persuade their sponsors to keep paying the bills. As a 21st century scientist, whose research funding would have vanished if I had failed to deliver on my promises for even a year or two, I am in awe. How did they do it? However, by the 17th century, the medieval worldview, in which alchemy made sense, was losing its grip on peoples’ imaginations, and many had come to believe that the only things alchemists were defending by the extravagant secrecy and occultism they regularly indulged in were their own livelihoods.

What is an element?

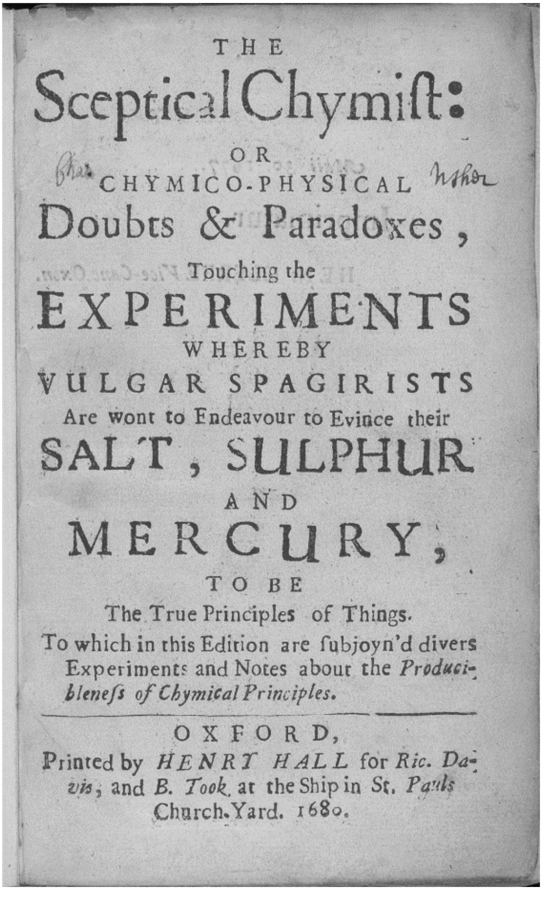
The conceptual problem that finally brought the alchemical tradition to its knees can be captured in a single word, "element", a term as well-known to the ancients and their alchemical successors as it is to us. The re-assessment of the meaning of that word that began in the second half of the 17th century led to the birth of the modern science of chemistry. Thus, in chemistry, elements are elemental in every sense of the word, and it is vital that you understand what chemists mean by that word.

Rooted deep in the human psyche is the sense—hope might be a better word—that the Universe is simpler than it looks. For ancient philosophers interested in substances, this idea was manifest in the concept of **elements**. Elements are substances from which non-elementary substances are made by combination, and they are elemental in the sense that they are composed of nothing but themselves; they cannot be generated by combining other substances together. That is what the ancients meant by the word “element”, and it is what chemists mean by it today.

The element concept is appealing. The colors of the solutions you can make by dissolving a red dye in water range from virtually colorless through various shades of pink and red, all the way to so-red-as-to-be-almost-black. If each colored solution is regarded as a substance in its own right, and the red dye and water are taken to be elements, one can understand how many different substances might be made by combining small numbers of elements together—whatever that means—and the more elements there are, the greater the number and the variety of the substances that might be made this way. Things multiply. Human intuition is seldom a reliable guide to the way the universe works, but in this instance, we got lucky. Elements exist. The concept is sound.

What has changed radically over time are our ideas about the number of elements, their identities, and the way non-elementary substances are produced from them. Taoists in China, for example, thought that everything in the world was made of five elements: water, wood, metal, earth, and fire. Greek philosophers, Aristotle prominent among them, favored a four-element universe: earth, air, fire and water. The objective of these philosophers was to explain why substances have the properties they do, and they asserted that the properties of non-elementary substances could be understood as blends of those possessed by the elements of which they are made.

It is important to recognize that the ancients used the concept of elements to solve two entirely different problems, one of them being the way the human sensory system responds to substances, and the other being the composition of matter. The retina of the human eye, for example, contains cells that respond preferentially either to red, green, or blue light, and we distinguish one color from another by comparing the outputs produced by these three classes of light-sensitive cells. Aristotle did not know this, but in effect, he was proposing that our brains respond to substances the same way, namely by sensing their relative degrees of earthiness, airiness, fieriness and wateriness. Be that as it may, nothing more will be said about the workings of the human sensory system here because it has nothing to do with the elemental compositions of substances. However, embedded in Aristotle’s hypothesis about sensory perception was a second hypothesis, namely that the reason humans respond to substances the way they do is that earth, air, fire and water are the ultimate constituents of matter; they are elements. This assertion has nothing to do with sensory perception as such, but everything to do with chemistry. It should be added, that if you believed Aristotle to be correct, as most medieval alchemists did, then the conversion of lead into gold ought to have been possible because neither was thought to be an element. All you had to do was figure out how to make it happen.



THE
Sceptical Chymiſt:
OR
CHYMICO-PHYSICAL
Doubts & Paradoxes,
Touching the
EXPERIMENTS
WHEREBY
VULGAR SPAGIRISTS
Are wont to Endeavour to Evince their
SALT, SULPHUR
AND
MERCURY,
TO BE
The True Principles of Things.
To which in this Edition are ſubjoyn'd divers Experiments and Notes about the *Producibleneſs of Chymical Principles.*

OXFORD,
Printed by *HENRY HALL* for *Ric. Davis*, and *B. Took*, at the Ship in St. *Pauls* Church-Yard. 1680.

Figure 1-1. Title page of *The Sceptical Chymist* by Robert Boyle. General Collection, Beineke Rare Book and Manuscript Library, Yale University.

Figure 1-1 is a facsimile of the title page of the 1680 edition of the book some regard as the foundational document for the science of chemistry; its first edition appeared in 1661. It presents Robert Boyle's view of the morass that had been created by centuries of sterile philosophical and alchemical speculation about substances. The book is written as a debate between several speakers, one of whom is the skeptical chymist (Boyle), and the others, advocates of one or another of the then fashionable theories about the ultimate nature of substances. *The Sceptical Chymist* is no fun to read because it assumes not only that the reader is acquainted with the alchemical theories it discusses, but also that he or she is familiar with seventeenth century chemical nomenclature, which can be colorful, but is often annoyingly obscure. For example, you will note that the title page refers to "vulgar spagirists". What is a spagirist, you ask, and are they all vulgar? Since nothing useful would come of elaborating on these points, we will move on.

Boyle is often credited with inventing the modern definition of elements, which is not quite true. What he did argue in *The Sceptical Chymist* was that the theories about the relationship between substances and elements that were in vogue in 1650 were inconsistent with observation. If all substances are composed of earth, air, fire then, for example, then the so-called "earth" obtained by making one substance react ought to be the same as the "earth" obtained from any other material, and that was plainly not so. In addition, it was as obvious to Boyle, as it has been to everyone since, that no matter how hard you bake, heat, distill or otherwise abuse gold you cannot extract anything from it that you might describe as earth, air, fire or water. Hence, Boyle argued, earth, air, fire and water cannot be elementary, but gold might be, and indeed, as we enlightened moderns know, fire isn't a substance at all. Boyle's attitude is clearly stated in a comment that appears in an essay he wrote prior to the publication of *The Skeptical Chymist*:

> "Until such times as someone analyzes gold and similar substances into three constituent parts I will not deny it to be possible absolutely … yet must I suspend my belief till either experience or competent testimony hath convinced me of it."

In the era in which Boyle was writing, the sciences as we know them today did not exist, and in these words, Boyle captures the essence of the enterprise that led to their creation. First, natural philosophers, i.e. scientists, were to set aside all of the theories about nature that had been advocated by the ancients; the slate was to be wiped clean. Second, experimental observation was to be the final arbiter of truth. Theories about the natural world were to be modified, if not abandoned entirely, if new experiments yielded results that were inconsistent with them. Third, theories were to be as simple as the facts allow.

This last requirement was not forced on natural philosophers by nature as much as by logic. It is a version of the philosophical principle called Occam's razor, and it is used to choose between competing theories that are equally consistent with the facts. It states that the best theory is the simplest theory.

Comment: William of Occam was a scholastic philosopher who lived in medieval England. Few would know of him today if his name had not become attached to this concept, and he is lucky it did because it is clearly stated in the writings of Ptolemy and Aristotle, both of whom were far more influential than he ever was.

It is critically important to realize that for Boyle—as for every chemist since—verbs like "analyze" were/are operationally defined. If a substance is capable of decomposing chemically at all, it will decompose if it is heated hot enough. In Boyle's time, the highest temperatures one could access were those produced by fires. For the record, the temperature of the flame produced by an oxyacetylene torch is ~3700° C, which is about the hottest flame there is, and much hotter than any of the flames available to Boyle. Thus, a (chemical) element is a substance that: (a) will not decompose when exposed to the flame of an oxyacetylene torch, and (b) cannot be produced by making other elements combine at similar temperatures, or below.

"Element" is not the only word or concept that scientists define operationally. Implicit in every scientific definition is an experiment that could be done to determine whether it is applicable to whatever it being used to describe. Furthermore, it is important to realize that advances in experimental methods and/or theoretical understanding sometimes require that definitions be modified.

It should also be pointed out that fire is produced by chemical reactions. Thus, the temperatures required to test whether a substance is elemental are generated chemically, and that means that the definition of the word "element" is circular. A substance is a (chemical) element if it cannot be made to decompose by chemical means, i.e. by means, the violence of which is less than or equal to that caused by the chemistry that occurs in an oxyacetylene flame, and if it cannot be produced from other substances by similar means. As we will see later, substances that are elementary in the chemical sense will decompose if the treatments to which they are subjected are more violent than that, and using similarly violent means, it is also possible to transform one elementary substance into another.

Over time, Boyle's insistence on the primacy of observation led those interested in chemical phenomena to alter the way elements are identified. Instead of relying on philosophy for guidance, they would rely on experiment. If you claim that a substance is not an element then you must show that it can be degraded into elements, and you must also demonstrate the existence of reactions that will result in its formation from those same elements. Boyle and his contemporaries referred to such substances as "perfectly mixt bodies", which is a wonderful locution. Today we call them **compounds**. Conversely, elements cannot be degraded into simpler substances, no matter how hard you try, provided you use only those resources that were available in the typical (al)chemical laboratory of Boyle’s time, and no reactions exist that lead to the formation of one element from others.

There were some troubling problems implicit in this approach to identifying elements. First, for the next 200 years or so, not only was the number of elements unknown, it was entirely possible that it would turn out to be very large, which would have been unsettling from Boyle’s point of view. What would have been gained conceptually if the properties of substances had to be explained by invoking the existence of thousands of different elements? Second, the experimental approach to defining elements does not even pretend to explain why compounds have the properties they do, let alone why our sensory systems respond to them the way they do, which are problems the Aristotelians thought they had solved. Third, when Boyle talked of elements, he was talking about the ultimate, irreducible constituents of matter. If Boyle were alive today, he might identify as elemental subatomic particles like quarks, rather than substances like iron and gold, which are made of them.

Nevertheless, by demanding that natural philosophers rely on experiment, Boyle and his sympathizers initiated the transformation of alchemy into chemistry. What they were saying was that the only sure way to discover the truth about the physical world is to do experiments that will make Nature reveal it to you. By so doing, Boyle was also demanding that alchemists learn from their failures. If after a thousand years of trying, you still cannot turn lead into gold, let alone synthesize an elixir that makes people immortal, maybe it is time to start questioning the validity of the theories that made you think that these things are possible.

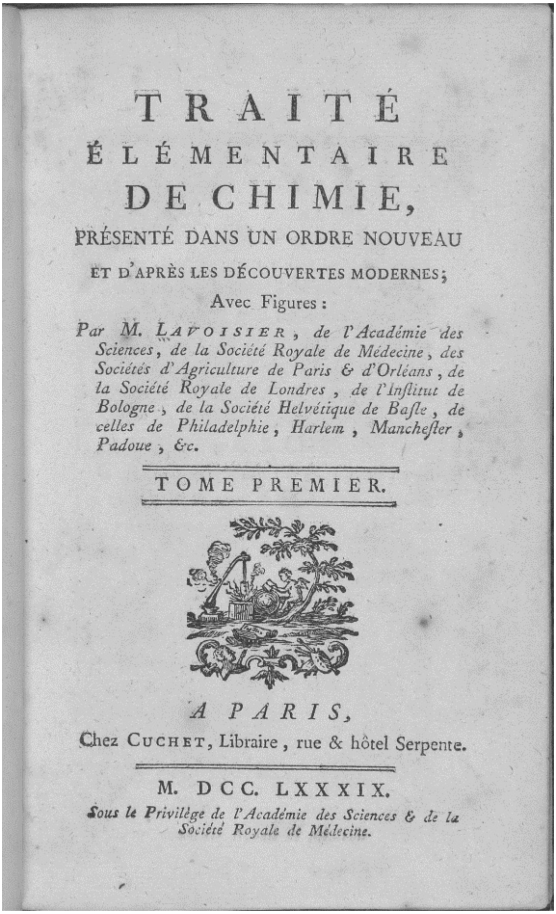
Three final comments are in order. First, by Boyle's criteria, which are the ones modern chemists honor, lead and gold are elements. Since elements cannot be inter-converted chemically, the alchemists' quest for the Philosophers Stone was doomed from the outset. Second, while it is true that elements can be inter-converted using non-chemical technologies developed by nuclear physicists over the past century, these processes are so expensive that no one will ever make money converting lead into gold this way, which is what those who financed the activities of alchemists hoped to do once the Philosopher’s Stone was in hand. Third, Boyle's followers were compelled to define elements based not on what they do, but rather on what they do not. Negative definitions are logically weak. One can never be sure whether the reason something fails to happen is because it cannot happen, or because you do not know how to make it happen. Sure enough, some of the substances identified as elements by those who followed Boyle turned out to be compounds that resist degradation.

Scientists have been searching for new elements since the time of Boyle. There are 118 known today, and the number is still slowly increasing. As you also probably know, some elements are radioactive, which means intrinsically unstable, a notion that would have astonished Boyle and many of his successors because, over time, radioactive elements spontaneously transform themselves into other elements, something that was thought to be impossible until evidence to the contrary began appearing around 1890. That said, eighty-one elements occur in nature in non-radioactive forms, which is to say in forms that are stable over periods of time that are long compared to the age of the Solar System. The remaining 37 elements are radioactive, but only a few of them are available in sufficient quantity to make them interesting from a practical point of view. Thus, the number of elements that really matter is about 85, and for reasons that will be explained later, it is certain that no more will ever be discovered. We have them all.

The mysteries of fire and air resolved

Just as the beginning of the transformation of alchemy into chemistry was marked by the publication of a book, *The Sceptical Chymist*, its end was announced by the publication of another book, *Traité Élémentaire de Chimie*, which appeared in 1789. It was written by Antoine-Laurent Lavoisier, and the difference between the two books is like night and day. The former deals with ideas that are alien to modern science for the most part, and it uses a vocabulary that makes it harder to read than Chaucer. Furthermore, even though some of the names used for substances in the *Traité* are archaic, it is a delight as well as being easy to read.

What happened between 1661, the date *The Sceptical Chymist* was published, and 1789, the year the *Traité* appeared, to make this transformation possible? Suffice it say that by 1789, the experimental method for determining which substances are elemental, which Boyle had advocated, was firmly established, and the list of elements had grown. Lavoisier's list included: light, caloric (heat), oxygen, azote (nitrogen), hydrogen, sulfur, phosphorus, charcoal (carbon), muriatic radical (chlorine), fluoric radical (fluorine), boracic radical, antimony, arsenic, bismuth, cobalt, copper, gold, iron, lead, manganese, mercury, molybdena, nickel, platina, silver, tin, tungsten, zinc, lime, magnesia, barytes, argilla (alumina), and silex (silica). The first two entries in his list, light and



TRAITÉ
ÉLÉMENTAIRE
DE CHIMIE,
PRÉSENTÉ DANS UN ORDRE NOUVEAU
ET D'APRÈS LES DÉCOUVERTES MODERNES;
Avec Figures:
Par M. Lavoisier, de l'Académie des Sciences, de la Société Royale de Médecine, des Sociétés d'Agriculture de Paris & d'Orléans, de la Société Royale de Londres, de l'Inſtitut de Bologne, de la Société Helvétique de Baſle, de celles de Philadelphie, Harlem, Mancheſter, Padoue, &c.

TOME PREMIER.

A PARIS,
Chez Cuchet, Libraire, rue & hôtel Serpente.

M. DCC. LXXXIX.
Sous le Privilège de l'Académie des Sciences & de la Société Royale de Médecine.

Figure 1-2: Title page of *Traité Élémentaire de Chimie* by Antoine Lavoisier. General Collection, Beineke Rare Book and Manuscript Library, Yale University.

caloric, remind us that in Lavoisier's time, the distinction between substances and energy was still poorly understood. Except for this (very) far from trivial issue, his list looks quite good. The substances Lavoisier called boracic radical, magnesia, barytes, argilla and silex are not elements, but they are all hard to degrade into their elements—they are refractory—and they all contain elements that do not appear elsewhere in the list: boron, magnesium, barium, aluminum and silicon, respectively.

The reason the list of elements had grown was that chemists had gotten better at quantitative analysis, which is the craft of determining the **elemental compositions** of substances. The elemental composition of a substance is the fraction of its weight that is accounted for by each of the elements it contains. One byproduct of this experimental advance was the custom of basing the names of compounds on their elemental compositions, a reform Lavoisier advocated and that is still adhered to. Thus, not long after Lavoisier, "muriatic acid" began to be called “hydrogen chloride” or “hydrochloric acid”, and "fixed air" became “carbon dioxide”. Interestingly, however, a handful of materials still retain their old, alchemical names, aqua regia being a good example. Aqua regia is a Latin phrase that means “royal water”, and it refers to mixtures of nitric acid and hydrochloric acid. Alchemists were intrigued by aqua regia because gold dissolves in it.

Encouraged by the Swedish chemist Jöns Berzelius, who was a younger contemporary of Lavoisier's, another important convention became established at about this time, namely the use of **symbols** based on the names of elements as a shorthand means of referring to them. His letter-based symbols replaced a variety of obscure symbol systems, some based on alchemical and astrological signs. In Berzelius’s system, which we still use, each element is identified by a symbol consisting of one or two letters (see Appendix 1). The first letter is always capitalized, and it is always the first letter of the element’s name in some language. The second letter, if there is one, is always a lowercase letter, and it is sometimes, but not always, the second letter of the element's name in that same language. The name from which an element’s symbol derives need not be its English name. For example, Fe, the symbol for iron, comes from *ferrum*, the Latin word for iron. The symbol for silver is Ag, which comes from the Latin word for silver, *argentum*, and the symbol for tungsten, W, derives from *wolfram*, the German word for tungsten.

Many of the reactions that interested Lavoisier and his contemporaries either consume gaseous substances, e.g. oxygen, or produce them, e.g. carbon dioxide. One of Lavoisier’s most important contributions to chemistry was his development of experimental techniques for measuring the masses of the gases consumed and/or produced during chemical reactions. This advance enabled him and his contemporaries to compare the masses of all the materials consumed in reactions to the masses of all the materials produced by them, no matter whether those substances were solids, liquids or gases. These comparisons led them to the critically important generalization about chemical reactions called **the law of the conservation of mass**, which states that when chemical reactions occur, the mass of the materials reacting (**reactants**) equals the mass of the materials produced (**products**).

Scientific laws are not to be confused with pieces of legislation, divine or otherwise. A scientific law is a generalization based on experimental observation for which no credible evidence exists to the contrary. In addition, scientific laws do not explain anything; they are statements of fact.

Like the definition of the word “element”, the law of the conservation of mass has limitations that derive from the kinds of observations on which it was based. The reader is probably aware that in the early years of the 20th century, Einstein discovered that every physical process that releases (or consumes) energy is associated with a decrease (or increase) in mass. The relationship between the mass change and the energy change of a process can be computed using his famous equation: $E = mc^2$. (If c, the speed of light, is measured in meters per second, and m in measured in kilograms, E will have the dimensions of joules (see Appendix 2)) Since energy changes accompany almost all chemical reactions, an example being the heat and light released when something burns, the mass of the reactants in a chemical reaction cannot be the same as the mass of the products obtained from them. Nevertheless, the law of the conservation of mass remains as useful to chemists today as it would have if Einstein had never been born, as can be demonstrated by working through a single example. When 1 kg of gasoline burns, i.e. reacts with oxygen, about 2.4×10^6 J of energy is released, which is a lot for a chemical reaction. The corresponding mass change, on the other hand, $\sim 2.7 \times 10^{-11}$ kg ($= 2.4 \times 10^6$ J$/(3 \times 10^8$ ms$^{-1})^2$), is not a lot. A modern, high-quality laboratory balance might be capable of measuring masses as large as 1 kilogram with an accuracy of $\pm 1 \times 10^{-6}$ kg, i.e. one part in a million. It would have to be five orders of magnitude more accurate than that to detect the difference in mass between 1 kg gasoline (plus the mass of the oxygen it takes to make it burn) and the products of its combustion. Thus, the energy-related mass changes associated with chemical reactions are so tiny compared to the masses of material involved that they cannot be measured using ordinary laboratory balances, which not only were the instruments used to arrive at