Second Edition

The Periodic Table

Its Story and Its Significance

Eric Scerri

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Dedication

I dedicate this book to my parents, Ines and Edward Scerri, for steering me toward the scholarly life. The book is also dedicated to my wife, Elisa Seidner, for her love and support and for helping to design the front cover.

Contents

Preface to the Second Edition

The publisher has requested that I update this book to coincide with 2019, the International Year of the Periodic Table (IYPT) that marks the 150th anniversary of Mendeleev's 1869 paper announcing the first fully mature periodic table. I have been anticipating a second edition for some time and have built up a large folder containing messages and letters from readers who have kindly pointed out typographical errors and various suggestions for improvements. I hope to have made as many of these improvements as possible, and, of course, I welcome any further suggestions to this ongoing project. My thanks to all those who have written to me during the 12-year period that has elapsed since the first edition appeared. Unfortunately, they are too numerous to name individually.

I have been very fortunate that the book has been generally well received and has been reviewed in more than 60 journals and magazines. These reviews have also served as guides to improvements. The book has been translated into several languages during which process it received close scrutiny from experts and translators, who also contributed to broadening my knowledge of many aspects of science and history of science that are discussed.

The new edition introduces four new chapters – two are completely new, some others have been reworked. First of all, chapter 10 of the earlier book consisted of a motley collection of topics, which some commentators rightly suggested should be separated. The material on "more chemistry" has now been removed to a separate chapter that serves to close the book. I think it helps to remember that, when all is said and done, the periodic table remains primarily in the domain of chemistry, although the relationship between chemistry and the underlying explanation from physics remains as the underlying theme of the book.

Similarly, the material on alternative forms of the periodic table that was in the original chapter 10 is now in another new chapter that is greatly expanded to review recent developments, such as the question of the placement of helium and the question of which elements belong to group 3 of the periodic table. These alternative forms of the periodic table continue to arouse interest from amateurs all the way to professional chemists, physicists, and philosophers of science and highlight the important point that the periodic table is by no means a *fait accompli*.

Chapter 9, on the quantum mechanical account of the periodic table, has now been greatly expanded to include some recent work on the perennial question of

the occupation and ionization of the 4s and 3d orbitals as well as the question of anomalous configurations, such as those that occur in the atoms of chromium and copper.

Two completely new chapters have then been added. The first of these chapters is on what I call the seven missing infra-uranium elements, that is, the seven elements that remained to be discovered between hydrogen and uranium, following the discovery of the concept of atomic number. Another new chapter consists of an account of the synthetic elements that have been "discovered," including the very recently named quartet of elements that serve to complete the seventh row of the table and indeed to complete the entire periodic table for the first and probably the last time in the foreseeable future. Needless to say, this is a somewhat artificial feature since it depends on which representation of the periodic table one is referring to. On the left-step periodic table, which is attracting increasing attention from periodic table scholars, the table will only become complete after elements 119 and 120 are synthesized.

The book ends with a compilation of all the references that appear in each chapter that have been collected together in alphabetical order for the convenience of the reader, as well as what is hopefully the most complete listing of books on elements and the periodic table in several languages. Finally I have added a list of my own articles on the periodic table as well as related concepts.

Eric Scerri
Los Angeles, 2019
www.ericscerri.com

New Credits

Credits for all newly introduced figures have been added to the figures and are not listed together as they were in the first edition.

Preface to the First Edition

This book has been in the making for about six years, although perhaps I should say about twenty years since it was that long ago that I undertook my Ph.D. at what was then Chelsea College, University of London, under the excellent supervision of the late Heinz Post. Of course, I could go back even further and mention that my love affair with the periodic table began when I was still in my teens and attending Walpole grammar school in the West London borough of Ealing.

Now that this book is completed, I have the opportunity to thank all those who contributed to it either directly or indirectly as colleagues or mentors at various stages of my own development. At Walpole grammar school, Mrs. Davis was the chemistry teacher who noticed that I was fooling around at the back of the class and ordered me to sit in the front row. At this point, I had no choice but to listen to the lesson, and I soon discovered that chemistry was rather interesting.

Moving on to Westfield College, which was part of the University of London, I had many wonderful professors, among them John Throssell and Bernard Aylett, a theoretician and an inorganic chemist, respectively. This was followed by a year of theoretical work at Cambridge under the great David Buckingham, who despaired of my asking too many philosophical questions. Then I moved to Southampton University, where I obtained a Master of Philosophy degree in Physical Chemistry with the inimitable Pat Hendra. At this point, I began teaching chemistry in high schools and tutorial colleges. I eventually went back to research and wrote my Ph.D. in history and philosophy and philosophy of science on the question of the reduction of chemistry to quantum mechanics. I cannot overestimate the debt that I owe to Heinz Post, and as all who know him recall, he was perhaps the nearest thing to the archcritic Wolfgang Pauli that ever graced the philosophy of science scene in the United Kingdom. Not that I ever witnessed Pauli, however.

It was Heinz Post who encouraged me to try to develop the philosophy of chemistry, which I have sought to do ever since. I think it was also Heinz who first planted the idea of my going to the United States to teach and carry out research. But before moving on to my story in the United States, let me pause to mention a few other folks in London who have been influential and helpful: Mike Melrose, a theoretical chemist from King's College, London, and John Worrall from the London School of Economics. It has been a great privilege to have subsequently coauthored an article with each of them.[1]

I went to the United States as a postdoctoral fellow at Caltech. Here I must thank my colleagues Diana Kormos-Buchwald, Fiona Cowie, Alan Hayek, and James Woodward in the Humanities Division. I subsequently went for a year to Bradley University in the heart of Illinois, where I was warmly received by Don Glover and Kurt Field, among others, in the chemistry department. Then followed another visiting professorship at Purdue University, where I interacted mainly with George Bodner and historian–chemist–educator Derek Davenport. In the year 2000, I moved to the chemistry department at UCLA, where I am blessed with numerous great colleagues, among others, Miguel Garcia-Garibay, Robin Garrell, Steve Hardinger, Ken Houk, Herb Kaesz, Richard Kaner, Laurence Lavelle, Tom Mason, Craig Merlic, and Harold Martinson.

In addition, I am grateful to all the members of the International Philosophy of Chemistry Society, which a small group of us founded in the early 1990s after we realized that there were a sufficient number of people with an interest in this field.[2] My thanks to Michael Akeroyd, Davis Baird, Nalini Bhushan, Paul Boogard, Joseph Earley, Rom Harré, Robin Hendry, David Knight, Mark Leach, Paul Needham, Mary Jo Nye, Jeff Ramsay, Joachim Schummer, Jaap van Brakel, Krishna Vemulapalli, Stephen Weininger, Michael Weisberg, and many others.

Perhaps the largest group to acknowledge consists of the many scholars of the periodic table from diverse fields, who include Peter Atkins, Henry Bent, Bernadette Bensaude, Nathan Brooks, Fernando Dufour, John Emsley, Michael Gordin, Ray Hefferlin, Bill Jensen, Masanori Kaji, Maurice Kibler, Bruce King, Mike Laing, Dennis Rouvray, Oliver Sachs, Mark Winters, and others.

I thank my various coeditors at Foundations of Chemistry, both past and present, including John Bloor, Carmen Giunta, Jeffrey Kovac, and Lee McIntyre. I thank my UCLA colleagues in the Department of Philosophy, including Calvin Normore, Sheldon Smith, and Chris Smeenk, and in the Department of History, Ted Porter and Norton Wise.

My thanks to members of various online discussion lists, including Chemed, History of Chemistry, Philchem, Hopos, and CCL (Computational Chemistry Listserver), with whom various points were ironed out, sometimes amidst heated debate.

Last but not least, there are a number of people who helped me specifically with the compilation of this book, especially with collecting photos and images. They include Ted Benfey, Gordon Woods, Ernst Homberg, Frenando Dufour, and Susan Zoske; George Helfand and Andreana Adler from the photographic unit at UCLA who scanned the diagrams; and Marion Peters in the chemistry department library. Special thanks to Daniel Contreras, who was always patient in helping me to unearth those obscure early sources. I am sure he grew quite tired of ordering volumes of *Science News* for me from the vaults on the other side of campus. Special thanks also go out to Goeffrey Rayner Canham and William Brock for their detailed comments on the entire manuscript and to Jan Van

Spronsen, the doyen of the periodic table, for his comments on some early chapters of the book.

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The Edgar Fahs Smith Collection at the University of Pennsylvania for providing photos and permission for use of photos of Cannizzaro, Dalton, Lavoisier, G.N. Lewis, and Ramsay, and for permission to use a photo of Lothar Meyer.

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Gordon Woods for providing the photo and permission for "The Consolidators of the Periodic Law."

Fernando Dufour for providing the photo of his own 3-D periodic system.

Article Credits

I have drawn from my own previous articles and particularly from four publications:

British Journal for the Philosophy of Science, 42, 309–325, 1991 (published by Oxford University Press, UK).

Annals of Science, 51, 137–150, 1994 (published by Taylor & Francis)

Studies in History and Philosophy of Science, 32, 47–452, 2001 (published by Elsevier)

Foundations of Chemistry, 6, 93–116, 2004 (published by Springer)

All these articles were used by permission from the publishers.

Notes

1. M.P. Melrose, E.R. Scerri, Why the 4s Orbital Is Occupied before the 3d, *Journal of Chemical Education*, 73, 498–503, 1996; E.R. Scerri, J. Worrall, Prediction and the Periodic Table, *Studies in the History and Philosophy of Science*, 32, 407–452, 2001.

2. At about the same time, the official journal of the society, *Foundations of Chemistry,* was also started.

Introduction

> As long as chemistry is studied there will be a periodic table. And even if someday we communicate with another part of the universe, we can be sure that one thing that both cultures will have in common is an ordered system of the elements that will be instantly recognizable by both intelligent life forms.
>
> J. Emsley, *The Elements*

The periodic table of the elements is one of the most powerful icons in science: a single document that captures the essence of chemistry in an elegant pattern. Indeed, nothing quite like it exists in biology or physics, or any other branch of science, for that matter. One sees periodic tables everywhere: in industrial labs, workshops, academic labs, and of course, lecture halls.

The Periodic System of the Elements

It is sometimes said that chemistry has no deep ideas, unlike physics, which can boast quantum mechanics and relativity, and biology, which has produced the theory of evolution. This view is mistaken, however, since there are in fact two big ideas in chemistry. They are chemical periodicity and chemical bonding, and they are deeply interconnected.

The observation that certain elements prefer to combine with specific kinds of elements prompted early chemists to classify the elements in tables of chemical affinity. Later these tables would lead, somewhat indirectly, to the discovery of the periodic system, perhaps the biggest idea in the whole of chemistry. Indeed, periodic tables arose partly through the attempts by Dmitri Mendeleev and numerous others to make sense of the way in which particular elements enter into chemical bonding.

The periodic table of the elements is a wonderful mnemonic and a tool that serves to organize the whole of chemistry. All of the various periodic tables that have been produced are attempts to depict the periodic system. The periodic system is so fundamental and all pervasive in the study of chemistry, as well as in professional research, that it is often taken for granted, as very familiar things in life so frequently are.

In spite of the central, or some might say homely, role of the periodic table, few authors have felt drawn to write books on its evolution. There is no book that deals adequately with the historical, and especially the conceptual, aspects of the periodic system or its significance in chemistry and science generally.[1] It is with the aim of injecting a more philosophical treatment to understanding the periodic system that the present work has been undertaken. I make no apologies for this approach, which I believe is long overdue and can perhaps be understood in the context of the almost complete neglect of the study of the philosophy of chemistry until its recent resurgence in the mid-1990s.

Only two major books on the periodic system have appeared in the English language, one of these being a translation from the Dutch original.[2] The more contemporary of these books, published in 1969 and authored by Johannes van Spronsen, is an excellent and detailed exposition of the history of the periodic system. One of the few omissions from van Spronsen's book is a discussion of the way in which modern physics is generally claimed to have explained the periodic system. Van Spronsen at times accepts the usual unspoken, or sometimes explicit, claim that the periodic system has been "reduced" to quantum mechanics, to use a phrase popular in philosophy of science.[3] In my own view, the extent to which quantum mechanics reduces the periodic system is frequently overemphasized. Of course, quantum mechanics provides a better explanation than was available from the classical theories of physics, but in some crucial respects the modern explanation is still lacking, as I hope to explain.

The only other serious treatise on the periodic system, written in English, is a masterly and detailed exposition, published in 1896, by F.P. Venable of the University of North Carolina–Chapel Hill.[4] It goes without saying that, for all its strengths, this book is severely limited, as it covers a period that ended more than 100 years ago, before modern physics began to exercise a major influence on the way the periodic system is understood.

There is also a compilation of more than 700 representations of the periodic system in a book by E. Mazurs, who devoted a lifetime of study to the topic. However, this book is neither a history nor a philosophy of the periodic system but a rather idiosyncratic attempt to develop a system of classification for periodic classifications themselves. It serves as a repository of the huge variety of forms in which the periodic system has been represented, and it is a testament to how expansive and energetic the quest for the ultimate form of the periodic system has been.[5] This quest appears to be with us to this day, an issue that will be taken up in later chapters. Another virtue of the Mazurs book is that it provides a wealth of references to the primary and secondary literature on the periodic system, although this, too, is now some 35 or so years out of date.[6] The textbook author Peter Atkins has published a short popular book on the periodic system.[7] There are also a number of books, including those by Puddephatt and Monaghan,[8] as well as by Cooper,[9] Pode,[10] and Sanderson,[11] which use the periodic system as a means of

presenting the chemistry of the elements but make little attempt to evaluate critically the foundational basis of the system. The continuing interest in the periodic system is further exemplified by the appearance of books aimed at the nonspecialist by Strathern, Sacks, Morris, Kean, Aldersey-Williams, and Gray.[12] Although the focus of these books is on chemistry generally, they contain sections on the development of the periodic system. Recently, M. Gordin has published a biography of Mendeleev, which is historically sensitive as well as scientifically accurate, and benefits from the author's first-hand knowledge of the original Russian documents.[13] In addition W.B. Jensen has published a translation of many of Mendeleev's key articles.[2]

The Elements

In this book I examine the concept of an element in some detail, starting from the views expressed by the ancient Greek philosophers and bringing us right up to modern times. Although this topic has seldom been discussed in the context of the evolution of the periodic system, it is difficult to fully understand the classification of the elements without first attempting to understand what an element is and how such a concept has changed over time. There is a sense in which ancient views on the nature of the elements have not been entirely rejected, although they have been changed considerably.

The study of the nature of elements and compounds is at the heart of much of Aristotle's philosophy of substance and matter and even his most general views of "being" and "becoming." This was also true of many of the pre-Socratic philosophers, who were the first to discuss and theorize about the elements. About 20 centuries later, the nature of the elements was a major issue in the revolution of chemistry. Antoine Lavoisier seems to have been one of the first chemists to renounce the metaphysical view of the elements, which he replaced with a form of empiricism, which considered only substances that could actually be isolated as elements. Elements in this latter sense of the term are often called "simple substances."[14]

This essentially philosophical question regarding the nature of elements returned and profoundly shaped the views of Mendeleev, who is arguably the leading discoverer of the periodic system. Indeed, it appears that Mendeleev may have been able to make more progress than some of his contemporaries, who were also developing periodic systems, because of his philosophical ideas about the nature of the elements. Even in the twentieth century, following the discovery of isotopes, fierce debates were waged on the nature and correct definition of the term "element."[15]

Mendeleev held a dual view on the nature of elements, whereby they could be regarded as unobservable basic substances and also as Lavoisier's simple substances at the same time. Mendeleev thus acknowledged one of the central mysteries running throughout the long history of chemistry, which is the question of how, if at all, the

elements survive in the compounds they form when they are combined together. For example, how can it be claimed that a poisonous gray metal like sodium is still present when it combines with a green poisonous gas chlorine, given that the compound formed, sodium chloride, or common table salt, is white and not only nonpoisonous but also essential for life? These are the kinds of questions the ancient Greek philosophers wrestled with while trying to understand the nature of matter and change. As I will show, such questions are still with us today, although some aspects of them have been explained by modern physical theory and the theories of chemical bonding.

Alchemy

Although in this book I briefly examine the nature of the elements, and of atomism from their earliest origins, not too much time is devoted to issues surrounding alchemy, for various reasons. First, the study of alchemy has been fraught with the obvious difficulties of trying to understand a complex set of practices spanning a number of areas, including what today would be considered religion, psychology, numerology, metallurgy, and so on. In addition, alchemical texts were frequently shrouded in deliberate mystery and obfuscation to protect the practitioners, who were regularly accused of being charlatans. Such mystery also served to restrict alchemical knowledge to a few initiates belonging to particular secret cults.

The question of whether modern chemistry is a direct outgrowth of alchemy, or whether alchemy's fundamental tenets had to be rejected in order for chemistry to get started, has been the source of much debate and continues to be disputed by scholars. All I do here is refer the reader to a few detailed treatments containing more serious discussion of this vast field of study.

One interesting aspect of this issue that has emerged in recent years is a questioning of the notion that the giants of modern science, such as Isaac Newton and Robert Boyle, turned their backs on alchemy. Starting about 40 years ago, historians of science, and Betty Jo Dobbs in particular, have argued rather persuasively that Newton was a dedicated alchemist and that he might even have devoted more time to this field than to his work in theoretical physics, for which he is now universally revered. More recently, Lawrence Principe has re-alchemized Boyle in a similar way that Dobbs had re-alchemized Newton.[16] Through painstaking analysis of Boyle's writing, Principe argues that, contrary to the accepted view, Boyle did not reject alchemical ways in his seminal book, *The Sceptical Chymist*. Indeed, Principe writes:

> We now see that Boyle himself in no way rejected transmutational alchemy but rather pursued it avidly and appropriated several of its theoretical principles.... Boyle was not as "modern" as we thought, nor alchemy as "ancient." What we are witnessing, then, is a rapprochement between what have been previously seen as two separate and irreconcilable halves of the history of chemistry.[17]

A Philosophical Approach

As I have already suggested, the study of the periodic system is philosophically important in several ways. Let me be a little more specific. For some time now, philosophers of science have realized that they have placed too much emphasis on the study of scientific theories and not enough on other important aspects of science, such as experimental work and scientific practice in general.[18] This has led many researchers to initiate the study of the philosophy of experimentation. But even within the philosophical investigation of theoretical work, there has been a growing sense that there is much more to scientific theorizing than just appealing to high-level theories.

In many cases, the theory in question is too difficult to apply, and so scientists tend to base their work on models and approximations. The full acceptance of this fact has produced a subdiscipline that studies the nature of scientific models.[19] And yet, as I argue in this book, the periodic table of chemistry is neither a theory nor a model but more akin to an "organizing principle," for want of a better term.[20] This book is partly an attempt to encourage philosophers of science to study the periodic table as an example of yet another scientific entity that does a lot of useful scientific work without being a theory.[21]

Another reason why the periodic table is philosophically important is that it provides an excellent testing ground for the question of whether chemistry is nothing but physics deep down or, as philosophers like to say, whether chemistry reduces to physics. But even asking such a question has become controversial in modern scholarship. The view that physics is the most fundamental of the sciences or, indeed, the very notion of one field being more fundamental than another one is under severe threat from disciplines such a literary criticism, cultural anthropology, and postmodern critiques of science.[22] Such issues have become highly controversial in recent times, producing what is perhaps the major debate in today's academic world, namely, the "science wars." Many scholars, scientists, and intellectuals find themselves pitted against each other over the question of whether science provides a form of objective truth or whether it is no more than a social construction not necessarily governed by the way the world actually is. The traditional view of scientific objectivity is increasingly regarded as a thing of the past, and some scholars are even prepared to embrace a form of relativism, or the view that all forms of knowledge are equally valid.[23]

But many others believe the question of fundamentalism and reduction can still be studied within the context of science. One can still consider the more modest question of whether chemistry reduces to its sister science of physics. This question can be approached in a scientific manner by examining the extent to which chemical models or, indeed, the periodic system, can be explained by the most basic theory of physics, namely, quantum mechanics. It is this question that forms the underlying theme for this entire book, and it is a question that is

addressed more and more explicitly in later chapters as the story reaches the impact of modern physical theories on our understanding of the periodic system.

The Evolution of the Periodic System

As I try to show in this book, several intermediate and anticipatory steps preceded every important stage in the development of the periodic system. Of all the major developments in the history of science, there may be no better example than that of the periodic system to argue against Thomas Kuhn's thesis that scientific progress occurs through a series of sharp revolutionary stages.[24] Indeed, Kuhn's insistence on the centrality of revolutions in the development of science and his efforts to single out revolutionary contributors has probably unwittingly contributed to the retention of a Whiggish history of science, whereby only the heroes count while blind alleys and failed attempts are written out of the story.[25]

Science is, above all, a collective endeavor involving a large variety of people working sometimes in teams, sometimes in isolation, sometimes aware of the work of their contemporaries and sometimes not.[26] When trying to examine the development of a system of knowledge such as the periodic system, it may be more important to look at the overall picture complete with wrinkles than to concentrate on who came first or whether a certain development really is an anticipation of a later one. Nevertheless, since priority issues are part of this fascinating story, in this book I try to give an account of some of the most important ones without claiming to provide the final word on any of the long-standing disputes.

Perhaps a further word on a different sense of the term "Whiggism" is appropriate. Since this book is not intended as a work of historical scholarship, there will be many instances in which the story will be driven by what eventually took place in the history of science. I make no apology for this approach since part of the interest is in trying to trace the development of the modern periodic system. For example, when discussing triads of elements, which were based on atomic weights, I will not avoid looking ahead to the use of atomic numbers to see what effects this change might have on the validity or otherwise of triads.

So without further delay, what follows is a brief synopsis of the chapters of the present book. I adopt a historical approach in order to convey the gradual evolution that has taken place around the chemical icon that is the periodic system. However, my primary concern is the evolution of concepts and ideas rather than trying to produce a work of detailed historical scholarship.[27] At times, I even use strictly ahistorical examples to illustrate particular points.

The book takes the reader on an interdisciplinary tour of the many areas of science that are connected with the periodic system, including physics, mathematics, computational methods, history and philosophy of science, and of course, chemistry. The story begins with the pre-Socratic philosophers in ancient Greece

and progresses through the birth of atomism and on to Aristotle's four elements of earth, water, fire, and air. By the Middle Ages, when the full impact of alchemy was reached, a few other elements, such as sulfur and mercury, were added to the list. But this book does not explore the state of chemical knowledge of the elements in the Middle Ages, early medicine, or Arabic chemistry, although these are important preliminaries to modern chemistry. Nor does it visit the theory of phlogiston, which was deposed by the chemical revolution; it merely examines Lavoisier's famous list of 37 fundamental substances.[28]

Instead, the story of the periodic system will take the plunge with the work of William Prout, Johann Döbereiner, Leopold Gmelin, and others who began to explore numerical relationships among the elements in addition to the previously known chemical analogies between them. We encounter the first true periodic system, which was the helical periodic system of Alexandre De Chancourtois, as well as the early periodic systems of William Odling, Gustavus Hinrichs, Jean-Baptiste André Dumas, Max Pettenkofer, John Newlands, and Julius Lothar Meyer, culminating with Mendeleev's tables and his deductions concerning existing as well as completely new elements. In each case, we look into some of the historical background involved as well as specific aspects of the periodic system proposed.

The discovery in the 1890s of the noble gases, a group of elements that did not initially appear to fit into the periodic system, is analyzed, as is the eventual resolution of this problem. The turn of the twentieth century saw the discovery of radioactivity, which led to new ideas about the structure of the atom from J.J. Thomson and Ernest Rutherford. Very soon, isotopes of many of the elements were discovered, and this produced a major challenge to the periodic system. Niels Bohr, Wolfgang Pauli, Erwin Schrödinger, and Werner Heisenberg, who provided the modern explanation of the periodic system in terms of orbiting electrons and quantum numbers, continued the invasion of physics into the understanding of the periodic table.

Whenever scientists are presented with a useful pattern or system of classification, it is only a matter of time before they begin to ask whether there may be some underlying explanation for the pattern. The periodic system is no exception. Attempts to produce explanations of the periodic system have led to major advances in areas of science other than chemistry, especially theoretical physics. The notion that the atom consists of a nucleus with electrons in orbit around it, which is taken for granted in modern science, originated when British physicist J.J. Thomson tried to explain the order of the elements displayed in the periodic table. Similarly, when Bohr, one of the founders of quantum mechanics, applied new ideas about the quantum of energy to the atom, he was specifically trying to obtain a deeper understanding of the periodic system of the elements.[29]

A few years later, Pauli produced his celebrated Exclusion Principle, which is now known to govern the behavior of all matter from materials used to make transistors to the matter in neutron stars. Pauli's original research, carried out in

atomic physics, was initially an attempt to explain the form of the periodic system and why the various electron shells of the atom can contain only specific numbers of electrons. In the process, Pauli produced one of the most general principles known to science. His Exclusion Principle tells us, in simple terms, that an electronic orbital can contain only two electrons, which must have antiparallel spins.[30] A careful analysis of this principle and other general principles of quantum mechanics has produced a new discipline of quantum chemistry, which nowadays is exploited in the development of new materials from superconductors to pharmaceutical drugs.

Now a word on the subject of chemical education. Two of the leading discoverers of the periodic system, Lothar Meyer and Mendeleev, were outstanding chemical educators who developed their versions of the periodic system while writing chemistry textbooks. One of the principal roles of the periodic table is as a teaching tool, given that it unifies so much chemical information and establishes unity amidst the diversity of chemical phenomena. In recent years, there has been a growing awareness that chemistry is being taught as though it were a subdiscipline of physics. This tendency has occurred because physics, in the form of quantum mechanics, has been successful in explaining many aspects of chemistry. But this success is frequently overemphasized.

Chemistry students are increasingly fed a diet of orbitals, electronic configurations, and other theoretical concepts instead of being exposed to the more tangible colors, smells, and even explosions of "real chemistry." Some authors advocate making chemical education more "chemical," while at the same time introducing students to the necessary concepts in modern physics. In such an endeavor, the periodic table can serve as an excellent link between macroscopic chemical properties and the underlying quantum mechanical explanations.

But in addition to any pedagogical implications, the relationship between chemistry and physics has become increasingly important in the philosophy of science. In particular, the recent growth of the philosophy of chemistry as a distinct subdiscipline has been based to some extent on examining the question of the reduction of chemical laws, chemical models, and representations, such as the periodic system, to fundamental physics.[31]

But even before the advent of the philosophy of chemistry, the question of the reduction of scientific theories to successor theories has been an important concern, as has the question of whether any of the special sciences reduce to basic physics. Broadly speaking, as the logical positivist approach to philosophy has been superseded, claims for the reduction of theories and fields of science have been increasingly challenged.[32] The failure to establish the full reduction of theories and the special sciences has been one reason for the demise of logical positivism in philosophy. But this failure of reduction in the manner prescribed by logical positivism has not led to the abandonment of another central tenet of logical positivism, namely, a belief in the unity of the sciences.[33]

In contemporary philosophy of science, the question of reduction is no longer approached in an axiomatic manner. It is rather pursued in a more naturalistic manner by examining the extent to which the periodic system, for example, can be deduced from the first principles of quantum mechanics. While this approach is still rigorous, it is not rigorous in the sense of using formal logic to establish the required connection.[34] It is rather by examining the extent to which the facts in the secondary science, if one must use such terms, can be deduced in an *ab initio* manner, to use a contemporary phrase, from computational chemistry. One needs to examine the way in which the Schrödinger Equation explains the structure of the periodic system, a topic that is specifically addressed in chapter 9. But leading up to these more contemporary developments, there were already claims made by Bohr, and on his behalf, that he had given a reduction of the periodic system using just the old quantum theory.[35] The story of the periodic system is inextricably linked with the increasing influence of modern physics upon chemistry. The question of reduction in many forms thus underlies the developments discussed in this book.

And even further back in the story of the periodic system, one can see the influence of numerical approaches dating back to Prout's hypothesis and Döbereiner's triads, both of which predate the discovery of the periodic system. Hence, it is not just chemistry that enables one to classify the elements but a combination of chemistry with the urge to reduce, in the most general Pythagorean sense of describing facts mathematically. The story of the periodic system is the story of the blending of chemistry, Pythagoreanism, and, most recently, quantum physics.

If one takes a realistic view concerning the periodic law, one might claim that there is a definite fact of the matter concerning the point at which approximate repetition occurs among the elements as the atomic number sequence increases. For example, the position of the element helium has led to a certain amount of debate. While most chemists insist that the element is a noble gas, an appeal to the electronic configuration of its atoms suggests that it might be placed among the alkaline earths. A chemist having an antirealist disposition on these issues might consider that the representation of the elements is a matter of convention and that there is no real fact of the matter concerning where helium and other troublesome elements should be placed. These issues will be discussed in chapter 10, which also considers the astrophysical origin of the elements as well as some unusual chemical regularities embodied in the periodic table.

The question of reduction raises another interesting issue concerning the reduction of chemistry to quantum mechanics. It appears that most chemists are quite willing to accept the reductive claims from physics insofar as it bestows greater theoretical underpinning upon chemistry. Nevertheless, in cases such as the positioning of helium, chemists retain the right to classify the element in chemical terms even at the risk of overruling the findings of the reducing science.

Along with the realist view of the periodic system, as referred to above, comes the question of whether to regard the elements as "natural kinds," meaning realistic scientific entities that are differentiated by nature itself rather than by our human attempts at classification.[36] This in turn opens up further dialogue with mainstream philosophy of science, which concerns itself with the question of natural kinds. In philosophy of biology, species have been deemed not to be natural kinds since biological species evolve over time. Many philosophers have sought to locate natural kinds at the chemical level.[37] Elements, in particular, are regarded by many as the quintessential natural kind term. To be gold is to possess atomic number 79 and vice versa. Natural kinds have been regularly invoked in the debates among philosophers of language concerning how linguistic terms such as "gold" or "water" refer to objects in the world. According to the influential Kripke-Putnam view, we are urged to take a scientific view of natural kind terms. The term "water," for example, is to be taken as denoting just what modern science stipulates water to be, which is usually taken to be molecules of H_2O. This approach raises many issues that continue to exercise contemporary philosophers of science. Water is not simply H_2O since it may contain impurities or may be present in ionized form, to cite just two of many objections that have been raised.[38] Even the notion that elements may be natural kinds has been criticized on the basis of the existence of isotopes of many elements. Not all atoms of gold have the same mass, and so it has been claimed that gold is not a unique natural kind.[39]

It appears that one of the best ways to explore the relationship between chemistry and modern physics is to consider the status of the periodic system.[40] Given the renewed interest in the philosophy of chemistry and in the periodic system itself,[41] a reassessment of these basic issues is now required, and this is attempted in the chapters of this book.

Notes

1. There have only been three conferences specifically on the periodic table. The first was held in 1969 as part of the celebrations commemorating the centenary of Mendeleev's famous table of 1869 [M. Verde (ed.), *Atti del Convegno Mendeleeviano*, Accademia delle Scienze di Torino, 1971]. The second was held as recently as 2003 in Banff, Canada [D. Rouvray, R.B. King (eds.), *The Periodic Table: Into the 21st Century*, Science Studies Press, Bristol, UK, 2004]. The third such conference took place in Cusco, Peru, in 2004 [E. Scerri, G. Restrepo, *Mendeleev to Oganesson*, Oxford University Press, New York, 2018]. Appropriately enough, the fourth international meeting will take place in 2019, the International Year of the Periodic Table, to celebrate the 150th anniversary of the publication of Mendeleev's table and will be in St. Petersburg, Russia.

2. I am referring to scholarly books on the periodic table. In addition, for a translation of Mendeleev's main journal articles, see W.B. Jensen, *Mendeleev on the Periodic Law, Selected Writings, 1869–1905*, Dover Publications, Mineola, NY, 2005.

3. J. van Spronsen, *The Periodic System of the Chemical Elements, the First One Hundred Years*, Elsevier, Amsterdam, 1969. I find it embarrassing to make this criticism given the enormous debt I owe to van Spronsen's wonderful book on the periodic system.

4. F.P. Venable, *The Development of the Periodic Law*, Chemical Publishing Co., Easton, PA, 1896.

5. E. Mazurs, *The Graphic Representation of the Periodic System During 100 Years*, University of Alabama Press, Tuscaloosa, 1974. In addition, Mazurs has given some arguments for the adoption of a symmetrical representation of the periodic system.

6. For a now somewhat dated bibliography of secondary articles on the periodic system, which emphasizes philosophical works, see E.R. Scerri, J. Edwards, Bibliography of Literature on the Periodic System, *Foundations of Chemistry*, 3, 183–196, 2001. A revised bibliography will appear soon in the same journal.

7. P.W. Atkins, *The Periodic Kingdom*, Basic Books, New York, 1995. Also see E.R. Scerri, A Critique of Atkins' Periodic Kingdom and Some Writings on Electronic Structure, *Foundations of Chemistry*, 1, 287–296, 1999.

8. R.J. Puddephatt, P.K. Monaghan, *The Periodic Table of the Elements*, Oxford University Press, Oxford, 1985.

9. D.G. Cooper, *The Periodic Table*, Plenum Press, New York, 1968.

10. J.S.F. Pode, *The Periodic Table: Experiment and Theory*, Wiley, New York, 1973.

11. R.T. Sanderson, *The Periodic Table of the Chemical Elements*, School Technical Publishers, Ann Arbor, MI, 1971.

12. P. Strathern, *Mendeleyev's Dream*, Thomas Dunne Books, New York, 2001; O. Sacks, *Uncle Tungsten*, Alfred Knopf, New York, 2001; R. Morris, *The Last Sorcerers: Atoms, Quarks and the Periodic Table*, Walker & Co., New York, 2003; S. Kean, *The Disappearing Spoon*, Little, Brown, New York, 2010; H. Aldersey-Williams, *Periodic Tales*, Penguin Viking, London, 2011; T. Gray, *The Elements*, Black Dog and Leventhal, New York, 2009.

13. M. Gordin, *A Well-Ordered Thing*, Basic Books, New York, 2004. A revised edition was published in 2019 by Princeton University Press under the same title.

14. Lavoisier did not fully renounce the idea of elements as principles, however. For example, he regarded heat light and oxygen as examples of such principles.

15. A collection of articles edited by Elena Ghibaudi and myself on the concept of "element" is currently in preparation and will be published by Oxford University Press.

16. B.J.T. Dobbs, M.C. Jacob, *Newton and the Culture of Newtonianism*, Humanity Books, Amherst, NY, 1998.

17. Lawrence Principe, *The Aspiring Adept: Robert Boyle and His Alchemical Quest: Including Boyle's "Lost" Dialogue on the Transmutation of Metals*, Princeton University Press, Princeton, NJ, 1998, quoted from p. 220.

18. A number of detailed studies on philosophical aspects of scientific experiments now exist, including David Gooding, Trevor Pinch, Simon Schaffer, *The Uses of Experiment: Studies in the Natural Sciences*, Cambridge University Press, New York, 1989; and Allan Franklin, *The Neglect of Experiment*, New York, Cambridge University Press, 1986.

19. E.g., the book on scientific models by the philosopher Nancy Cartwright, *How the Laws of Physics Lie*, Oxford University Press, Oxford, 1983.

20. My disagreement with authors who believe the periodic table to be a theory is expressed in E.R. Scerri, A Critique of Weisberg's "Who Is a Modeler?" *Foundations of Chemistry*, 14, 275–284, 2012.

21. D. Shapere, Scientific Theories and Their Domains, in F. Suppe (ed.), *The Structure of Scientific Theories*, Illinois University Press, Urbana, 518–599.

22. The literature in this area has grown tremendously in recent years. For discussions, see P.R. Gross, N. Levitt, *Higher Superstition*, Johns Hopkins University Press, Baltimore, MD, 1994; A. Sokal, Transgressing the Boundaries: Towards a Transformative Hermaneutics of Quantum Gravity, *Social Text*, 46–47, 217–252, 1996; J.A. Labinger, H. Collins, *The One Culture*? University of Chicago Press, Chicago, 2001.

23. G. Bodner, M. Klobuchar, D. Geelan, The Many Forms of Constructivism, *Journal of Chemical Education*, 78, 1107–1134, 2001. For a critical appraisal, see E.R. Scerri, Philosophical Confusion in Chemical Education Research, *Journal of Chemical Education*, 80, 468–474, 2003.

24. This is not to imply that Kuhn himself or anyone else I am aware of has argued that the development of the periodic system *did* represent a scientific revolution. On a related point, in a recent book I have argued that there are very few, if any, Kuhnian revolutions in science in general, and I have proposed an evolutionary account of the development of science. Eric Scerri, *A Tale of Seven Scientists and a New Philosophy of Science*, Oxford University Press, New York, 2016.

25. Related claims about Kuhn's conservatism are made in Steve Fuller, *Thomas Kuhn: A Philosophical History for Our Times*, University of Chicago Press, Chicago, 2000; and Mara Beller, *Quantum Dialogue: The Making of a Revolution*, University of Chicago Press, Chicago, 1999.

26. I have written a book that addresses this question and that criticizes Kuhn's view of revolutions in science. The study is based on the work of seven little-known scientists and amateurs who made significant contributions to early-twentieth-century chemistry and atomic physics. E. Scerri, *A Tale of Seven Scientists and a New Philosophy of Science*, Oxford University Press, New York, 2016.

27. Readers interested in scholarly research on Mendeleev in particular should consult the work of a number of excellent contemporary historians of science, including N. Brookes, Developing the Periodic Law: Mendeleev's Work during 1869–1871, *Foundations of Chemistry*, 4, 127–147, 2002; M. Gordin, *A Well-Ordered Thing*, Basic Books, New York, 2004; and M. Kaji, Mendeleev's Discovery of the Periodic Table, *Foundations of Chemistry*, 5, 189–214, 2003.

28. Over the past 30–40 years, there has been a great deal of debate among historians of chemistry regarding Lavoisier's role in the chemical revolution and whether this was indeed a revolution or just the culmination of previous work begun by the likes of Georg Stahl. See articles by Gough, Siegfried, Perrin, and Holmes in A. Donovan (ed.), Chemical Revolution: Essays in Reinterpretation, *Osiris*, 2nd series, vol. 4, 1988.

29. The popular story found in most books is that Bohr was primarily concerned with explaining the spectrum of the hydrogen atom. But as Kuhn and Heilbron have convincingly argued, Bohr was not even aware of the problems with atomic spectra when he began applying quantum theory to the structure of the atom. T.S. Kuhn, J. Heilbron, The Genesis of the Bohr Atom, *Historical Studies in the Physical Sciences*, 3, 160–184, 1969.

30. Nevertheless, elementary particles do not literally spin in the way that the earth or a mechanical top does. A better description would be a classically nondescribable duplicity in the intrinsic angular momentum of electrons, which is indeed how Pauli first described what later became known simply as "spin."

31. My more recent thinking on this subject can be found in E. Scerri, The Changing Views of a Philosopher of Chemistry on the Question of Reduction, in E.R. Scerri, G. Fisher (eds.), *Essays in the Philosophy of Chemistry*, Oxford University Press, New York, 2016.

32. J.D. Trout, i n R. Boyd, P. Gaspar, J.D. Trout (eds.), Reduction and the Unity of Science, *The Philosophy of Science*, MIT Press, Cambridge, MA, 1992, 387–392.

33. A few modern commentators appear to disagree in this respect and regularly advertise their support for the "disunity of science": J. Dupré, *The Disorder of Things, Metaphysical Foundations of the Disunity of Science*, Harvard University Press, Cambridge, MA, 1993; N. Cartwright, *How the Laws of Physics Lie*, Clarendon Press, Oxford, 1983; N. Cartwright, *Nature's Capacities and Their Measurement*, Oxford University Press, Oxford,

1989; P. Galison, D. Stump, *The Disunity of Science*, Stanford University Press, Palo Alto, CA, 1996.

34. For a more detailed treatment of this modern approach to the reduction of chemistry, see E.R. Scerri, Popper's Naturalized Approach to the Reduction of Chemistry, *International Studies in Philosophy of Science*, 12, 33–44, 1998.

35. K.R. Popper, Scientific Reduction and the Essential Incompleteness of All Science, in F.L. Ayala, T. Dobzhansky (eds.), *Studies in the Philosophy of Biology*, Berkeley University Press, Berkeley, CA, 1974, 259–284.

36. Zdenka Brzovic, Natural Kinds, *The Internet Encyclopedia of Philosophy*, ISSN 2161–0002, 2018. http://www.iep.utm.edu/nat-kind.

37. J. LaPorte, Chemical Kind Terms, Reference and the Discovery of Essence, *Noûs*, 30, 112–132, 1996; J. LaPorte, *Natural Kinds and Conceptual Change*, Cambridge University Press, New York, 2004.

38. J. van Brakel, *Philosophy of Chemistry*, Leuven University Press, Leuven, Belgium, 2000.

39. I believe that this criticism can be countered by appeal to the elements as basic substances in the sense used by Mendeleev. E.R. Scerri, Some Aspects of the Metaphysics of Chemistry and the Nature of the Elements, *Hyle*, 11, 2, 2005.

40. P. Bernal, Foundations of Chemistry: Special Issue on the Periodic System, *Journal of Chemical Education*, 79, 1420, 2002.

41. E.g., see an editorial in *Foundations of Chemistry* for the special issue on the periodic system, vol. 3, 97–104, 2001.

The Periodic Table

CHAPTER

1

The Periodic System

The Elements

In ancient Greek times, philosophers recognized just four elements—earth, water, air, and fire—all of which survive in the astrological classification of the 12 signs of the zodiac. At least some of these philosophers believed that these different elements consisted of microscopic components with differing shapes and that this explained the various properties of the elements. These shapes or structures were believed to be in the form of Platonic solids (figure 1.1) made up entirely of the same two-dimensional shape. The Greeks believed that earth consisted of microscopic cubic particles, which explained why it was difficult to move earth. Meanwhile, the liquidity of water was explained by an appeal to the smoother shape possessed by the icosahedron, while fire was said to be painful to the touch because it consisted of the sharp particles in the form of tetrahedra. Air was thought to consist of octahedra since that was the only remaining Platonic solid. A little later, a fifth Platonic solid, the dodecahedron, was discovered, and this led to the proposal that there might be a fifth element or "quintessence," which also became known as ether.

Although the notion that elements are made up of Platonic solids is regarded as incorrect from a modern point of view, it is the origin of the very fruitful notion that macroscopic properties of substances are governed by the structures of the microscopic components of which they are comprised. These "elements" survived well into the Middle Ages and beyond, augmented with a few others discovered by the alchemists, the precursors of modern-day chemists. One of the many goals of the alchemists seems to have been the transmutation of elements. Not surprisingly, perhaps, the particular transmutation that most enticed them was the attempt to change the base metal lead into the noble metal gold, whose unusual color, rarity,

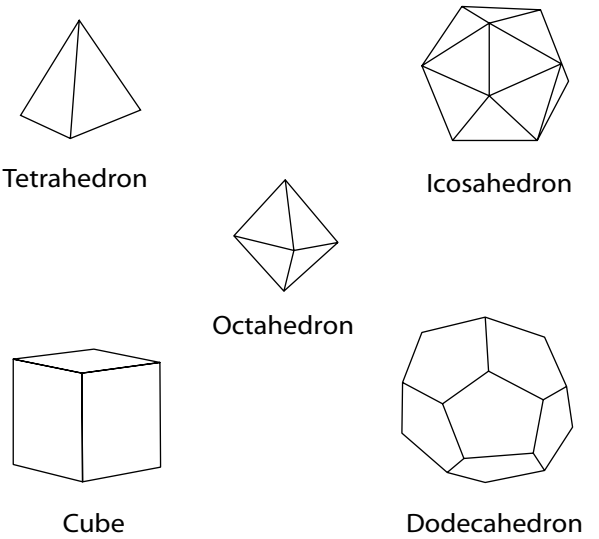
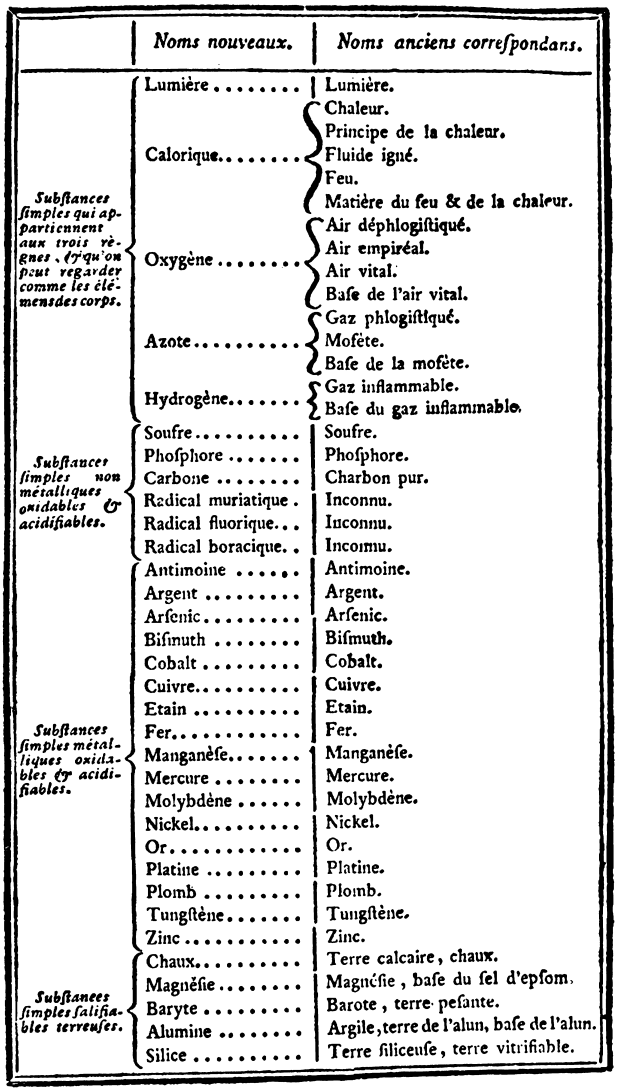


FIGURE 1.1 The five Platonic solids. O. Benfey, Precursors and Cocursors of the Mendeleev table: The Pythagorean Spirit in Element Classification, courtesy *Bulletin for the History of Chemistry*, 13-14, 60–66, 1992-93, figure from p. 60 (by permission).

and chemical inertness have made it one of the most treasured substances since the dawn of civilization.

The earliest understanding of the term "element" among the Greek philosophers was of a "tendency" or "potentiality" that gave rise to the observable properties of the element. This rather subtle distinction between the abstract form of an element and its observable form has been all but forgotten in modern times. It has nonetheless served as a fundamental guiding principle to such noted contributors to the periodic system as Dmitri Mendeleev, its major discoverer.

According to most textbook accounts, chemistry began in earnest only when it turned its back on alchemy and on this seemingly mystical understanding of the nature of elements. The triumph of modern science is generally regarded as resting on direct experimentation and the adoption of an empiricist outlook, which holds that only that which can be observed should count. Not surprisingly, therefore, the more subtle and perhaps more fundamental sense of the concept of elements was rejected. For example, Robert Boyle and Antoine Lavoisier both took the view that an element should be defined by an appeal to empirical observations, thus denying the role of abstract elements.[1] They recommended that an element should be defined as a material substance that has yet to be broken down into any more fundamental components by chemical means. In 1789, Lavoisier published a list of 33 simple substances or elements according to this empiricist criterion (figure 1.2).[2]



	Noms nouveaux.	Noms anciens correſpondans.
Subſtances ſimples qui appartiennent aux trois règnes, & qu'on peut regarder comme les élémens des corps.	Lumière	Lumière.
	Calorique	Chaleur. Principe de la chaleur. Fluide igné. Feu. Matière du feu & de la chaleur.
	Oxygène	Air déphlogiſtiqué. Air empiréal. Air vital. Baſe de l'air vital.
	Azote	Gaz phlogiſtiqué. Moſète. Baſe de la moſète.
	Hydrogène	Gaz inflammable. Baſe du gaz inflammable.
Subſtances ſimples non métalliques oxidables & acidifiables.	Soufre	Soufre.
	Phoſphore	Phoſphore.
	Carbone	Charbon pur.
	Radical muriatique	Inconnu.
	Radical fluorique	Inconnu.
	Radical boracique	Inconnu.
Subſtances ſimples métalliques oxidables & acidifiables.	Antimoine	Antimoine.
	Argent	Argent.
	Arſenic	Arſenic.
	Biſmuth	Biſmuth.
	Cobalt	Cobalt.
	Cuivre	Cuivre.
	Etain	Etain.
	Fer	Fer.
	Manganèſe	Manganèſe.
	Mercure	Mercure.
	Molybdène	Molybdène.
	Nickel	Nickel.
	Or	Or.
	Platine	Platine.
	Plomb	Plomb.
	Tungſtène	Tungſtène.
	Zinc	Zinc.
Subſtances ſimples ſalifiables terreuſes.	Chaux	Terre calcaire, chaux.
	Magnéſie	Magnéſie, baſe du ſel d'epſom.
	Baryte	Barote, terre peſante.
	Alumine	Argile, terre de l'alun, baſe de l'alun.
	Silice	Terre ſiliceuſe, terre vitrifiable.

FIGURE 1.2
List of 33 simple substances compiled by Lavoisier. *Traité Elémentaire de Chimie*, Cuchet, Paris, 1789, p. 192.

Gone were the ancient elements of earth, water, air, and fire, which had by now been shown to consist of simpler substances.[3]

Many of these substances would qualify as elements by modern standards, while others, such as *lumière* (light) and *calorique* (heat), are certainly no longer regarded as elements.[4] Rapid advances in techniques of separation and characterization of chemical substances over the forthcoming years would help chemists expand and refine this list. The important technique of spectroscopy, which measures the emission and absorption spectra of various kinds of radiation, would eventually yield a very accurate means by which each element could be identified

through its unique "fingerprint." In modern times, we recognize 94 naturally occurring elements, and it has even been possible to extend the range of the elements beyond those that occur naturally.[5]

The Discovery of the Elements

The story of the discovery of the elements is a fascinating one and has been the subject of at least one classic account.[6] A time line for the discoveries is given in table 1.1. This story is not systematically addressed in the present book, although references to predictions and discovery of elements are made throughout.[7]

TABLE 1.1
Discovery time line for the elements and approximate dates of contributions from major chemists and physicists connected with the periodic system.

Antiquity	Au, Ag, Cu, Fe, Sn, Pb, Sb, Hg, S, C	
Middle Ages	As, Bi, Zn, P, Pt	
1700		
1710		
1720		
1730	Co	
1740		
1750	Ni, Mg	
1760	H	
1770	N, O, Cl, Mn, Ba	
1780	Mo, W, Te, Zr, U	Lavoisier
1790	Ti Y, Be	
1800	V, Nb, Ta, Rh, Pd, Os, Ir, Ce	Dalton, Avogadro
	K, Na, B, Ca, Sr, Ru, Ba	Davy
1810	I, Th, Li, Se, Cd	
1820	Si, Al, Br	Döbereiner
1830	La	
1840	Er	Gmelin
1850		Cannizzaro
1860	Cs, Rb, Tl, In, He	Mendeleev, Lothar Meyer
1870	Ga, Ho, Yb, Sc, Tm	
1880	Gd, Pr, Nd, Ge, F, Dy	
1890	Ar, He, Kr, Ne, Xe, Po, Ra, Ac	Ramsay, Rayleigh
1900	Rn, Eu, Lu	Thomson
1910	Pa	Lewis, van den Broek, Moseley
1920	Hf, Re, Tc, Ma	Bohr, Pauli, Schrödinger
1930	Fr	
1940	Np, At, Pu, Cm, Am, Pm, Bk	Seaborg

Table 1.1
(*Continued*)

1950	Cf, Es, Fm, Md, No
1960	Lr, Rf, Db
1970	Sg
1980	Bh, Mt, Hs
1990	Ds, Rg, Cn, Fl
2000	Lv, Og, Mc, Ts
2010	Nh

Compiled by the author.

There have been a number of major episodes in the history of chemistry when half a dozen or so elements were discovered almost at once, or within a period of a few years. Of course, some elements, such as iron, copper, gold, and other metals, have been known since antiquity. Indeed, historians and archeologists refer to certain epochs in human history as the Iron Age or the Copper Age. The alchemists added several more elements to the list, including sulfur, mercury, and phosphorus. In relatively modern times, the discovery of electricity enabled chemists to isolate many of the more reactive elements that, unlike copper and iron, could not be obtained by heating their ores with carbon. The English chemist Humphry Davy seized upon the use of electricity or, more specifically, electrolysis to isolate as many as 10 elements, including calcium, barium, magnesium, sodium, and chlorine.[8]

Following the discovery of radioactivity and nuclear fission, and the development of techniques in radiochemistry, it became possible to fill the remaining few gaps in the periodic table. The last gap to be filled was that corresponding to element 43, which became known as technetium from the Greek *techne*, meaning artificial or manufactured. It was "manufactured" in the course of some radiochemical reactions that would not have been feasible before the advent of nuclear physics. More recently, it was claimed that the Noddacks may in fact have synthesized element 43 as they claimed, although this attempted rehabilitation has been refuted.[9]

The most recent spate of elemental discoveries is also based on technological developments, involving the production and harnessing of beams of pure atoms or pure elementary particles such as neutrons. These particles can be fired at each other with great precision to achieve nuclear fusion reactions and to thereby create new elements with extremely high atomic numbers. One of the initiators of this field was the American chemist Glenn Seaborg, who first synthesized plutonium in 1943 and went on to head research teams that were responsible for the synthesis of 10 transuranium elements.

Names and Symbols of the Modern Elements

Part of the appeal of the periodic table derives from the individual nature of the elements and from their names.[10] The chemist and concentration camp survivor

Primo Levi began each chapter of his much-acclaimed book *The Periodic Table*[11] with a vivid description of an element such as gold, lead, or oxygen. The book itself is about his relations and acquaintances, but each anecdote is motivated by Levi's love of a particular element.[12] More recently, the well-known neurologist and author Oliver Sacks wrote a book called *Uncle Tungsten*, in which he told of his boyhood fascination with chemistry and in particular the periodic table.[13]

During the many centuries over which the elements have been discovered, many different themes have been used to select their names.[14] Just reading a list of the names of elements can conjure up episodes from Greek mythology. Promethium, element 61, takes its name from Prometheus, the god who stole fire from heaven and gave it to human beings, only to be punished for this act by Zeus.[15] The connection of this tale to element 61 seems to be the extreme effort that was needed to isolate it, just as the task performed by Prometheus was difficult and dangerous. Promethium is one of the very few elements that was not thought to occur naturally on the earth. It was initially obtained as a decay product from the fission of another element, uranium.

Planets and other celestial bodies have been used to name some elements. For example, palladium, which was discovered in 1803, is named after Pallas, or the second asteroid that was itself discovered just one year earlier in 1802. Helium is named after *helios*, the Greek name for the sun. It was first observed in the spectrum of the sun in 1868, and it was not until 1895 that it was first identified in terrestrial samples.

Many elements derive their names from colors. Cesium is named after the Latin color *caesium*, which means gray-blue, because it has prominent gray-blue lines in its spectrum. The yellow-green gas chlorine comes from the Greek word *khloros*, which denotes the color yellow-green.[16] The salts of the element rhodium often have a pink color, and this explains why the name of the element was chosen from *rhodon*, the Greek for rose. In cases of more recently synthesized elements, their names come from those of the discoverer or a person whom the discoverers wish to honor. This is why we have bohrium, curium, einsteinium, fermium, gadolinium, lawrencium, meitnerium, mendeleevium, nobelium, roentgenium, rutherfordium, seaborgium and, most recently, oganesson.[17]

A large number of elements' names have come from the place where their discoverer lived, or wished to honor: americium, berkelium, californium, darmstadtium, europium, francium, germanium, hassium, nihonium, polonium, gallium, hafnium, moscovium, lutetium, rhenium, ruthenium, scandium and tennessine. Yet other element names are derived from geographical locations connected with minerals in which they were found. This category includes the remarkable case of four elements named after the Swedish village of Ytterby, which lies close to Stockholm. Erbium, terbium, ytterbium, and yttrium were all found in ores located around this village, while a fifth element, holmium, was named after the Latin for Stockholm.

The naming of the later trans-uranium elements is a separate story in itself, complete with nationalistic controversies and, in some cases, acrimonious disputes over who first synthesized the element and should therefore be accorded the honor of selecting a name for it. In an attempt to resolve such disputes, the International Union of Pure and Applied Chemistry (IUPAC) decreed that the elements should be named impartially and systematically with the Latin numerals for the atomic number of the element in each case. Element 105, for example, would be known as un-nil-pentium, while element 106 would be un-nil-hexium. But more recently, after much deliberation over the true discoverers of some of these later superheavy elements, IUPAC has returned the naming rights to the discoverers or synthesizers who were judged to have established priority in each case. Instead of their impersonal Latin names, elements 117 and 118, for example, are now called tennessine and oganesson, respectively.[18]

Seaborgium is a particularly interesting case, since for many years the committee did not approve of the choice of the American chemist Glenn Seaborg's name, even though he had been responsible for the synthesis of about 10 new elements, including number 106. Their official reason seems to have been an old rule that required that no element could be named after a person still living.[19] Following much campaigning by chemists in the United States and other parts of the world, Seaborg was finally granted his element while he was still alive.

Another curious case concerns the German chemist Otto Hahn, whose name was unofficially given to the element hahnium, only to be removed later and changed to the name dubnium after the place where several trans-uranium elements were synthesized. Meanwhile, an element has been named after Hahn's one-time colleague Lise Meitner. To many observers, this is a just move since Hahn had been awarded the Nobel Prize for the discovery of nuclear fission while Meitner, who had participated in many of the crucial steps in the work, was denied the prize.[20]

The symbols that are used to depict each element in the periodic table also have a rich and interesting story. In alchemical times, the symbols for the elements often coincided with those of the planets from which they were named or with which they were associated (figure 1.3). The element mercury, for example, shared the same symbol as that of Mercury, the innermost planetary body. Copper was associated with the planet Venus, and both the element and the planet shared the same symbol.

When John Dalton published his atomic theory in 1805, he retained several of the alchemical symbols for the elements. These were rather cumbersome, however, and did not lend themselves easily to reproduction in articles and books. The modern use of simple letter symbols was introduced by the Swedish chemist Jacob Berzelius a little later, in 1813.

In the modern periodic table, a small minority of elements are represented by a single letter of the alphabet. These include hydrogen, carbon, oxygen, nitrogen,

Metal							
	gold	silver	iron	mercury	tin	copper	lead
Symbol							
	☉	☾	♂	☿	♃	♀	♄
Celestial Body							
	Sun	Moon	Mars	Mercury	Jupiter	Venus	Saturn
Day							
Lat.	(*dies*)						
	Solis	*Lunae*	*Martis*	*Mercurii*	*Jovis* (*pater*)	*Veneris*	*Saturni*
Fr.	*dimanche*	*lundi*	*mardi*	*mercredi*	*jeudi*	*vendredi*	*samdi*
Eng.	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday

FIGURE 1.3 Names and symbols of the ancient metals compared to names of celestial bodies and days of the week. V. Rignes, *Journal of Chemical Education*, 66, 731–738, 1989, p. 731 (by permission).

sulfur, and fluorine, which appear as H, C, O, N, S, and F, respectively.[21] Most elements are depicted by two letters, the first of which is a capital letter and the second a lowercase letter. This gives rise to such element symbols as Li, Be, Ne, Ca, and Sc, for lithium, beryllium, neon, calcium, and scandium, respectively. Some of these two-letter symbols are by no means intuitively obvious, such as Cu, Na, Fe, Pb, Hg, Ag, and Au, which are derived from the Latin names for the elements copper, sodium, iron, lead, mercury, silver, and gold.[22] Tungsten is represented by a W after the German name for the element, which is *wolfram*. In fact, for the first and probably the last time, there are no missing elements in the periodic table, although this situation will only persist until a new 8th period will begin when element 119 is synthesized.[23]

The Modern Periodic Table

The manner in which the elements are arranged in rows and columns in the modern periodic table, also called the medium-long form (figure 1.4), reveals many relationships among them. Some of these relationships are very well known, while others still await discovery. To take just one example, in the 1990s scientists discovered that the property of superconductivity, the flow of current with zero resistance, could be observed at relatively high temperatures of about 100 Kelvin. This discovery was partly serendipitous. When the elements lanthanum, copper, oxygen, and barium were combined together in a particular manner, the resulting compound happened to display high-temperature superconductivity. There followed a flurry of worldwide activity in an effort to raise the temperature at which the effect could be maintained. The ultimate goal was to achieve room-temperature superconductivity, which would allow technological breakthroughs such as levitating

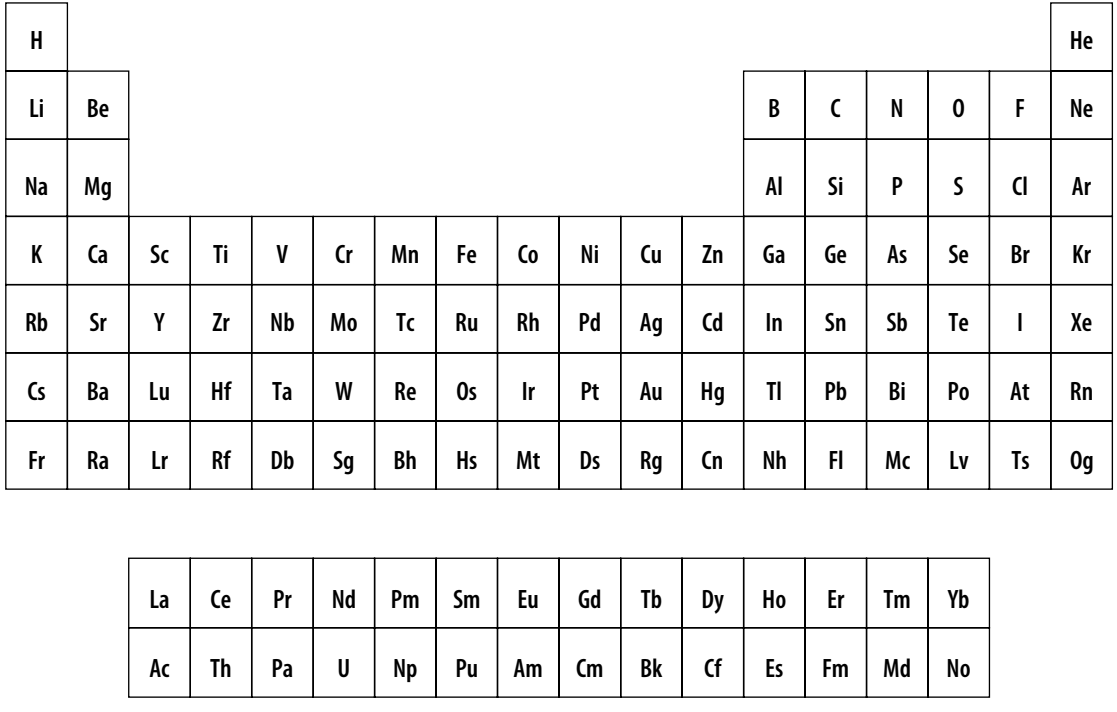


FIGURE 1.4 The modern or medium-long form table.

trains gliding effortlessly along superconducting rails. One of the main guiding principles used in this quest was the periodic table of the elements. The table allowed researchers to replace some of the elements in the compound with others that are known to behave in a similar manner and then examine the effect on superconducting behavior. This is how the element yttrium was incorporated into a new set of superconducting compounds, to produce the compound $YBa_2Cu_3O_7$ with a superconducting temperature of 93K.[24] This knowledge, and undoubtedly much more, lie dormant within the periodic system, waiting to be discovered and put to good use.

The conventional periodic table consists of rows and columns. Trends can be observed among the elements going across and down the table. Each horizontal row represents a single period of the table. On crossing a period, one passes from metals such as potassium and calcium on the left, through transition metals such as iron, cobalt, and nickel, then through some semimetallic elements such as germanium, and on to some nonmetals such as arsenic, selenium, and bromine on the right side of the table. In general, there is a smooth gradation in chemical and physical properties as a period is crossed, but exceptions to this general rule abound and make the study of chemistry a fascinating and unpredictably complex field.

Metals themselves can vary from soft dull solids such as sodium or potassium to hard shiny substances such as chromium, platinum, and gold. Nonmetals, on the other hand, tend to be solids or gases, such as carbon and oxygen, respectively. In terms of their appearance, it is sometimes difficult to distinguish between solid metals and solid nonmetals. To the layperson, a hard and shiny metal may seem to be more metallic than a soft metal such as sodium. But in a chemical sense, elements that have the greater ability to lose electrons (lower ionization energies) are regarded as being the more metallic. Sodium is therefore regarded by chemists as being more metallic than such elements as iron or copper. The periodic trend from metals to nonmetals is repeated with each period, such that when the rows are stacked they form columns, or groups, of similar elements. Elements within a single group tend to share many important physical and chemical properties, although there are many exceptions.

The manner in which the groups in the modern periodic table are labeled is complicated and controversial. The groups, or columns, of main-group elements, which are also referred to as representative elements, lie on the extreme left and right of the modern periodic table. In the United States, these groups were generally labeled with Roman numerals from I to VIII, with the letter A sometimes added to differentiate them from transition metals or groups IB to VIIIB, which lie in the central portion of the table. However, in Europe the convention was different in that all groups are sequentially labeled from left to right as IA to VIIIA until one reached the group headed by copper, where the labeling becomes IB up to the noble gases, which were said to be in group VIIIB (figure 1.5).[25] Both of these systems used the same Roman numeral for each column, which, in the case of main-group elements, also denotes the number of outer-shell electrons.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VIIB	—	VIIIB	—	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
IA	IIA	IIIA	IVA	VA	VIA	VIIA	—	VIIIA	—	IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIIIB
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

FIGURE 1.5 Diagram of conventional periodic table format with alternative numbering systems for groups: the more recent IUPAC system (top line), US system (second line), and European system (third line). Note that 3 columns are labeled as VIII in the US European system but each column has a distinct number in the IUPAC system.

Given the confusion that these conventions have caused, there has been much attention directed at obtaining a unified system. In 1990, IUPAC recommended that groups should be sequentially numbered with Arabic numerals from left to right, as groups 1 to 18, without the use of the letters A or B. The unfortunate result of this proposal is that the direct correlation between the number of outer-shell electrons in the atoms of main-group elements and the group labels in the old US and European systems is lost. For example, the atom of oxygen has six outer-shell electrons and is said to be in group VI (followed by an A or a B) in the older systems, whereas in the IUPAC system it is considered to be in group 16. As a result, although many textbooks display the IUPAC recommendation on periodic tables, they generally fail to adhere to it when discussing the properties of the elements.[26]

This book mainly uses Roman numerals for the representative or main-group elements and refers to transition metal groups by the name of their first element. For example, group IVA in the US system (carbon, silicon, germanium, tin, and lead) is referred to as simply group IV. Meanwhile, group VIB in the US system (chromium, molybdenum, and tungsten) is referred to as the chromium group. Nevertheless, in some chapters the IUPAC system of numbering groups is used to avoid any possible confusion.

And so with this proviso, the extreme left of the table, group I contains such elements as the metals sodium, potassium, and rubidium. These are unusually soft and reactive substances, quite unlike what are normally considered metals, such as iron, chromium, gold, and silver. The metals of group I are so reactive that merely placing a small piece of one of them into pure water gives rise to a vigorous reaction that produces hydrogen gas and leaves behind a colorless alkaline solution.[27] The elements in group II include magnesium, calcium, and barium and tend to be less reactive than those of group I in most respects.

Moving to the right, one encounters a central rectangular block of elements collectively known as the transition metals, which include such examples as iron, copper, and zinc. In early periodic tables, known as short-form tables (figure 1.6), these elements were placed among the groups of what are now called the main-group elements. Several valuable features of the chemistry of these elements are lost in the modern table because of the manner in which they have been separated from the main body of the table, although the advantages of this later organization outweigh these losses.[28] To the right of the transition metals, in the medium-long form table, lies another block of representative elements starting with group III and ending with group VIII, the noble gases on the extreme right of the table.

Sometimes the properties a group shares are not immediately obvious. This is the case with group IV, which consists of carbon, silicon, germanium, tin, and lead. Here one notices a great diversity on progressing down the group. Carbon, at the head of the group, is a nonmetal solid that occurs in three completely different structural forms (diamond, graphite, and fullerenes)[29] and forms the basis of all

преимущественно найдти общую систему элементовъ. Вотъ этотъ опытъ:

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4
			Fe=56	Ru=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

FIGURE 1.6 Short-form table. The original Mendeleev's table published in 1869, D.I. Mnendeleev, Sootnoshenie svoistv s atomnym vesom elementov, *Zhurnal Russkeo Fiziko-Khimicheskoe Obshchestv,* 1, 60–77, 1869, table from p. 70.

living systems. The next element below, silicon, is a semimetal that, interestingly, may form the basis of artificial life, or at least "artificial intelligence," since it lies at the heart of all computers. The next element down, germanium, is a more recently discovered semimetal that was predicted by Mendeleev and later found to have many of the properties he foresaw. On moving down to tin and lead, one arrives at two metals known since antiquity. In spite of this wide variation among them, in terms of metal–nonmetal behavior, the elements of group IV nevertheless are similar in an important chemical sense in that they all display a maximum combining power, or valence, of 4.[30]

The apparent diversity of the elements in group VII is even more pronounced. The elements fluorine and chlorine, which head the group, are both poisonous gases. The next member, bromine, is one of the only two known elements that exist as a liquid at room temperature, the other one being the metal mercury.[31] Moving further down the group, one then encounters iodine, a violet-black solid element.[32] If a novice chemist were asked to group these elements according to their appearances, it is inconceivable that he or she would consider classifying together fluorine, chlorine, bromine, and iodine. This is one instance where the subtle distinction between the observable and the abstract sense of the concept of an element can be helpful. The similarity between them lies primarily in the nature of the abstract elements and not the elements as substances that can be isolated and observed.[33]

On moving all the way to the right, a remarkable group of elements, the noble gases, is encountered, all of which were first isolated just before, or at, the turn of

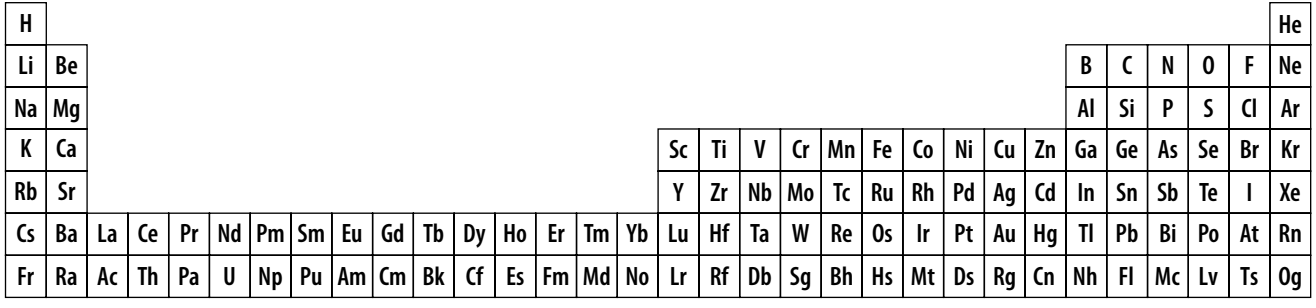


FIGURE 1.7 Long-form periodic table.

the twentieth century.[34] Their main property, rather paradoxically, at least when they were first isolated, was that they lacked chemical properties.[35] These elements, which include helium, neon, argon, and krypton, were not even included in early periodic tables, since they were unknown and generally unanticipated. When they were discovered, their existence posed a formidable challenge to the periodic system, but one that was eventually successfully accommodated by extension of the table to include a new group, labeled group VIII or group 18 in the IUPAC system.

Another block of elements, found at the foot of the modern table, consists of the lanthanides and actinides that are commonly depicted as being literally disconnected. But this is just an apparent feature of this generally used display of the periodic system. Just as the transition metals are generally inserted as a block into the main body of the table, it is quite possible to do the same with the lanthanides and actinides. Indeed, many such long-form displays have been published. While the long-form tables (figure 1.7) give these elements a more natural place among the rest of the elements, they are rather cumbersome and do not readily lend themselves to conveniently shaped wall charts of the periodic system. Although there are a number of different forms of the periodic table, what underlies the entire edifice, no matter the form of its representation, is the periodic law.

The Periodic Law

The periodic law states that after certain regular but varying intervals the chemical elements show an approximate repetition in their properties. For example, fluorine, chlorine, and bromine, which all fall into group VII, share the property of forming white crystalline salts of general formula NaX with the metal sodium. This periodic repetition of properties is the essential fact that underlies all aspects of the periodic system.

This talk of the periodic law raises some interesting philosophical issues. First of all, periodicity among the elements is neither constant nor exact. In the generally used medium-long form of the periodic table, the first row has two elements, the second and third each contains eight, the fourth and fifth contain 18, and so on. This implies a varying periodicity consisting of 3, 9, 9, 19, and so on,[36] quite unlike the kind of periodicity one finds in the days of the week or notes in a musical scale. In these latter cases, the period length is constant, such as eight for the days of the week as well as the number of notes on a Western musical scale.

Among the elements, however, not only does the period length vary, but also the periodicity is not exact. The elements within any column of the periodic table are not exact recurrences of each other. In this respect, their periodicity is not unlike the musical scale, in which one returns to a note denoted by the same letter, which sounds like the original note but is definitely not identical to it, being an octave higher.

The varying length of the periods of elements and the approximate nature of the repetition have caused some chemists to abandon the term "law" in connection with chemical periodicity. Chemical periodicity may not seem as lawlike as the laws of physics, but whether this fact is of great importance is a matter of debate.[37] It can be argued that chemical periodicity offers an example of a typically chemical law, approximate and complex, but still fundamentally displaying lawlike behavior.[38]

Perhaps this is a good place to discuss some other points of terminology. How is a periodic table different from a periodic system? The term "periodic system" is the more general of the two. The periodic system is the more abstract notion that holds that there is a fundamental relationship among the elements. Once it becomes a matter of displaying the periodic system, one can choose a three-dimensional arrangement, a circular shape, or any number of different two-dimensional tables. Of course, the term "table" strictly implies a two-dimensional dimensional representation.[39] So, although the term "periodic table" is by far the best known of the three terms "law," "system," and "table," it is actually the most restricted.

Reacting Elements and Ordering the Elements

Much of what is known about the elements has been learned from the way they react with other elements and from their bonding properties. The metals on the left-hand side of the conventional periodic table are the complementary opposites of the nonmetals, which tend to lie toward the right-hand side. This is so because, in modern terms, metals form positive ions by the loss of electrons, while nonmetals gain electrons to form negative ions. Such oppositely charged ions combine together to form neutrally charged salts such as sodium chloride or calcium bromide. There are further complementary aspects of metals and nonmetals. Metal oxides or hydroxides dissolve in water to form bases, while nonmetal oxides or hydroxides dissolve in water to form acids. An acid and a base react together in a "neutralization" reaction to form a salt and water. Bases and acids, just like metals and nonmetals from which they are formed, are also opposite but complementary.[40]

Acids and bases have a connection with the origins of the periodic system since they featured prominently in the concept of equivalent weights, which was first used to order the elements. The equivalent weight of any particular metal, for example, was originally obtained from the amount of metal that reacts with a certain amount of a chosen standard acid. The term "equivalent weight" was subsequently generalized to denote the amount of an element that reacts with a standard amount of oxygen. Historically, the ordering of the elements across periods was determined by equivalent weight, then later by atomic weight, and eventually by atomic number.[41]

Chemists first began to make quantitative comparisons among the amounts of acids and bases that reacted together. This procedure was then extended to reactions between acids and metals. This allowed chemists to order the metals on a numerical scale according to their equivalent weight, which, as mentioned, is just the amount of the metal that combines with a fixed amount of acid. The concept of equivalent weights is, at least in principle, an empirical one since it seems not to rest on the theoretical assumption that the elements are ultimately composed of atoms.[42]

Atomic weights, as distinct from equivalent weights, were first obtained in the early 1800s by John Dalton, who indirectly inferred them from measurements on the masses of the relevant elements combined together. But there were complications in this apparently simple method that forced Dalton to make assumptions about the chemical formulas of the compounds in question. The key to this question is the valence, or combining power, of an element. For example, a univalent atom combines with hydrogen atoms in a ratio of 1:1; divalent atoms, such as oxygen, combine in a ratio of 2:1; and so on.

Equivalent weight, as mentioned above, is sometimes regarded as a purely empirical concept since it does not seem to depend upon whether one believes in the existence of atoms. Following the introduction of atomic weights, many chemists who felt uneasy about the notion of atoms attempted to revert to the older concept of equivalent weights. They believed that equivalent weights would be purely empirical and therefore more reliable. But as many authors have argued, most recently Alan Rocke, such hopes were an illusion since equivalent weights also rested on the assumption of particular formulas for compounds, and formulas are theoretical notions.

For many years, there was a great deal of confusion created by the alternative use of equivalent weight and atomic weight. Dalton himself assumed that water consisted of one atom of hydrogen combined with one atom of oxygen, which would make its atomic weight and equivalent weight the same, but his guess at the valence of oxygen turned out to be incorrect. Many authors used the terms "equivalent weight" and "atomic weight" interchangeably, thus further adding to the confusion. The true relationship between equivalent weight, atomic weight, and valency was clearly established only in 1860 at the first major scientific conference, which was held in Karlsruhe, Germany.[43] This clarification and the general adoption of consistent atomic weights cleared the path for the independent discovery of the periodic system by as many as six individuals in various countries, who each proposed forms of the periodic table that were successful to varying degrees. Each placed the elements generally in order of increasing atomic weight.[44]

The third, and most modern, of the ordering concepts mentioned above is atomic number. Once atomic number was understood, it displaced atomic weight as the ordering principle for the elements. No longer dependent on combining weights in any way, atomic number can be given a simple microscopic interpretation in terms of the

structure of the atoms of any element. The atomic number of an element is given by the number of protons, or units of positive charge, in the nucleus of any of its atoms. Thus, each element on the periodic table has one more proton than the element preceding it. Since the number of neutrons in the nucleus also tends to increase as one moves through the periodic table, this makes atomic number and atomic weight approximately proportional, but it is atomic number that identifies any element. This is to say that atoms of any particular element always have the same number of protons, although they can differ in the number of neutrons they contain.[45]

Different Representations of the Periodic System

The modern periodic system succeeds remarkably well in ordering the elements by atomic number in such a way that they fall into natural groups, but this system can be represented in more than one way. Thus, there are many forms of the periodic table, some designed for different uses. Whereas a chemist might favor a form that highlights the reactivity of the elements, an electrical engineer might wish to focus on similarities and patterns in electrical conductivities.[46]

The way in which the periodic system is displayed is a fascinating issue, and one that especially appeals to the popular imagination. Since the time of the early periodic tables of John Newlands, Julius Lothar Meyer and Dmitri Mendeleev, there have been many attempts to obtain the "ultimate" periodic table. Indeed, it has been estimated that within 150 years of the introduction of Mendeleev's famous table of 1869, approximately 1000 different versions of the periodic table have been published. These include all kinds of alternatives, including three-dimensional tables, helices, concentric circles, spirals, zigzags, step tables, and mirror image tables.[47]

What is fundamental to all these attempts is the periodic *law* itself, which exists in only one form. None of the multitude of displays changes this aspect of the periodic system. Many chemists stress that it does not matter how this law is physically represented, provided that certain basic requirements are met. Nevertheless, from a philosophical point of view, it may still be relevant to consider the most fundamental representation of the elements, or the ultimate form of the periodic system, especially as this relates to the question of whether the periodic law should be regarded in a realistic manner or as a matter of convention.[48] The usual response that representation is only a matter of convention would seem to clash with the realist notion that there may be a fact of the matter concerning the points at which the repetitions in properties occur.[49]

Recent Changes in the Periodic Table

In 1945, Glenn Seaborg (figure 1.8) suggested that the elements beginning with actinium, number 89, should be considered as a series analogous to the lanthanides,

FIGURE 1.8
Glen Seaborg. Photo from Emilio Segrè Collection, by permission.

whereas it had previously been supposed that such elements would begin after element 92, or uranium (figure 1.9). Seaborg's new periodic table revealed an analogy between europium (63) and gadolinium (64) and the as yet undiscovered elements 95 and 96, respectively. On the basis of these analogies, Seaborg succeeded in synthesizing and identifying the two new elements, which were subsequently named americium and curium. A number of further trans-uranium elements have subsequently been synthesized.[50]

The standard form of the periodic table has also undergone some minor changes regarding the elements that mark the beginning of the third and fourth rows of the transition elements. Whereas older periodic tables show these elements to be lanthanum (57) and actinium (89), more recent experimental evidence and analysis have put lutetium (71) and lawrencium (103) in their former places.[51] It is also interesting to note that some even older periodic tables based on macroscopic properties had anticipated these changes.

These are examples of ambiguities in what may be termed secondary classification, which is not as unequivocal as primary classification, or the sequential ordering of the elements. In classical chemical terms, secondary classification corresponds to the chemical similarities between the various elements in a group. Meanwhile, in modern terms, secondary classification is explained by recourse to the concept of electronic configurations. Regardless of whether one takes a classical qualitative chemical approach or a more physical approach based on electronic configurations, secondary classification of this type is more tenuous than primary classification and cannot be established as categorically.[52] The way in which secondary classification, as defined here, is established is a modern example of the

																H	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	RE	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	AC	Th	Pa	U												

rare earths	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

																H	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	LA	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	AC															

La	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Ac	Th	Pa	U	Np	Pu									

FIGURE 1.9 Pre-Seaborg (a) and post-Seaborg (b) periodic tables. RE denotes rare earth elements from 57–71 inclusive; LA, lanthanides (Z = 57–71); AC, actinides beginning with Z = 89, where Z is atomic number.