Logic, History, and the Chemistry Textbook

III. One Chemical Revolution or Three?

William B. Jensen
Department of Chemistry, University of Cincinnati, Cincinnati, OH 45221-0172

The following is the third of three invited keynote lectures given at the 57th annual summer conference of the New England Association of Chemistry Teachers held in August of 1995 at Sacred Heart University in Fairfield, Connecticut. Lectures I and II have appeared in earlier issues of the Journal (1).

In this, our third and final lecture, I want to outline for you how the logic table, introduced in Lecture I, mirrors the historical development of modern chemistry. That the current state of chemistry should reflect its historical evolution is no more surprising than the fact that the present-day culture of a country or the anatomy of a living organism is also a reflection of its historical evolution. However, we must be on guard against the ever-present temptation to reverse this dependency and to assume that chemists have always been consciously struggling toward the current structure of chemistry. Though biology accepts the premise that the structure and behavior of present-day organisms can be used as a guide to uncovering their biological evolution, it does not accept the premise that this current structure and behavior represent a unique teleological goal toward which earlier organisms were either consciously or unconsciously striving.

History is not a predictive science, and attempts to make it so have almost always devolved into ideological and political nightmares (2). It deals rather with the retrospective description of what is almost always a unique and irreproducible path of development. Though I suspect that much of this development is the result of random, or at least highly-contingent events, the human mind requires that knowledge be organized in some manner. In the case of history, we almost always use the present as a way of organizing and structuring the past and, in so doing, we naturally place the greatest emphasis on those aspects that have survived to the present day. As humans we require the familiar as a touchstone in exploring the unfamiliar. In this way the present serves as a reference state that allows us both to sift the important from the ephemeral and to more thoroughly appreciate, through a nonjudgmental comparison with our reference state, those features of the past that have failed to survive. Whether the resulting historical order is real or merely an artificial construct imposed on the chaos of history by some defect in the human mind, is a matter I will leave to others to decide.

As in the case of all classification schemes, our logic table oversimplifies. Classification is based on abstracting certain characteristics and overlooking others. Consequently it almost always ignores a certain inherent fuzziness in its categorical boundaries that results from the overlap of one class with another. In using our logic table to impose an organizational structure on the evolution of modern chemistry, we run much the same risk. Time periods that are represented as distinct, often overlap, etc. These are inherent defects common to all attempts at organization and classification, whether of natural objects, concepts, models, or historical events. As A. C. Candler once said (3):

... historical divisions are arbitrary ... periods really overlap and intertwine, but it is necessary to be arbitrary in order to be clear.

With these caveats in mind, let us begin by briefly reviewing some earlier organizational frameworks that have been used to describe the history of chemistry, after which we will outline the alternative picture suggested by our logic table.

Approaches to the History of Chemistry

Histories of chemistry are legion. In his 1974 bibliographic study, Jost Weyer listed no fewer than 71 general histories of chemistry written between 1561 and 1970, of which 29, or roughly 40%, have appeared in English (4). These figures do not include specialized histories of various subdisciplines, such as organic or analytical chemistry, or the equally voluminous literature dealing with the history of alchemy. Prior to the chemical revolution, these histories made little attempt to divide events into significant historical periods or eras. An exception was the 1779 essay, “On the Origin of Chemistry”, by the Swedish chemist Torbern Bergman in which he rather quaintly suggested that the history of chemistry could be “properly divided into the mythologic, the obscure, and the certain” (5). Though I am sure that many of our students would concur, but with the proviso that we have as yet to enter the era of certainty, such a division obviously lacks precision.

By the end of the 18th century, however, it was apparent that the work of Antoine Lavoisier represented a fundamental watershed that separated a new era of “modern chemistry” from an earlier era of so-called “protochemistry”, and historians began the task of resolving this protochemical era into several significant periods. Thus Lavoisier’s colleague and propagandist, Antoine Fourcroy, used six distinct divisions in the historical chapter of his 1782 text, *Leçons élémentaire d’histoire naturelle et de chimie* (6):

1. Greco–Egyptian Origins (Pre-9th Century AD)
2. The Chemistry of the Arabians (800–1000 AD)
3. European Alchemy (1000–1500)
4. Pharmaceutical Chemistry (1500–1650)
5. Philosophical Chemistry (1650–1750)
6. Pneumatic Chemistry (Post-1750)

By 1843, the German chemist and historian Hermann Kopp, in his epic four-volume *Geschichte der Chemie*, had regrouped Fourcroy’s Greco–Egyptian, Arabian, and European periods into one large alchemical period, separated out a true ancient
or pre-alchemical period, and relabeled (with slight revisions of the time frame) the pharmacological, philosophical and pneumatic periods:

1. Ancient (Pre-4th Century AD)
2. The Age of Alchemy (350–1525 AD)
3. The Age of Medicinal Chemistry (1525–1650)
4. The Phlogistonic Period (1650–1775)
5. The Age of Quantitative Investigation (Post-1775)

Further Modifications of the Protochemical Era

With few exceptions, modern histories of chemistry have continued to use Kopp’s divisions. Minor changes include a more explicit emphasis on the separation of alchemy into distinctive Hellenic, Islamic, and European periods, the relabeling of the medicinal chemistry period as the period of iatrochemistry, and the relabeling of the early quantitative period as the chemical revolution.

One of the few alternatives to this scheme was proposed by the American historian of chemistry Aaron Ihde in an article written in 1956. He suggested that the division of the protochemical era into successive individual periods was too linear and that modern chemistry was best viewed as the product of three contributing streams or “pillars” (Fig. 1)—alchemy, medicine, and metallurgy—which acted simultaneously, rather than consecutively, throughout the entire protochemical period, though the significance of the role played by each fluctuated with time.

I personally prefer to use a compromise model that I call the “converging stream model” (Fig. 2) in which, as time progresses, more and more contributing influences or streams are added to the protochemical data base that serves as the foundation of modern chemistry. Like Fourcray, I also feel that the transition from protochemistry to modern or “philosophical” chemistry takes place before Lavoisier’s revolution and corresponds to the period when chemists began to view chemistry not as a source of religious and mystical metaphors (as was the case with alchemy) or as a practical adjunct to the practice of medicine and pharmacy (as was the case with iatrochemistry) but rather as an abstract science of matter. In other words, it corresponds to a significant change in attitude concerning the nature and function of chemistry rather than to a significant theoretical breakthrough. This clearly occurs by the middle of the 17th century and is quite explicit in the writings of Robert Boyle. This criterion places both the so-called phlogistonic period and the mechanical chemistry advocated by Boyle himself (however unfruitful their theoretical constructs may have been) within the era of modern chemistry. In keeping with this, I have taken the 1660s—the decade which saw the publication of Boyle’s most famous book, The Sceptical Chemist—as an arbitrary dividing line separating the protochemical and modern chemical periods.

Modifications of the Modern Chemical Era

When Kopp wrote his classic history, his final era of “Quantitative Investigation” encompassed fewer than 75 years (i.e., from 1775 to 1843). Today it spans more than 220 years. Despite this, modern histories of chemistry have made almost no attempt to further subdivide it into significant periods. In general, after discussing the nature of Lavoisier’s revolution, they treat the early development of atomic theory and electrochemistry and then revert to an organization based on the rise of special subdisciplines—most notably organic chemistry (in the period 1820–1874) and physical chemistry (in the period 1880–1920), with a possible update on inorganic chemistry at mid-century (via the periodic table and the rise of coordination theory). With the exception of Aaron Ihde’s book, *The Development of Modern Chemistry*, no history currently in print has a substantive discussion of developments after 1920.

Can we do better than this? Is there some way of giving a structure to that part of the arrow in the converging stream model that lies above the line labeled “chemical revolution”? What I would like to suggest to you in the rest of this lecture is that our earlier discussion of the logical structure of mod-

![Figure 1. Ihde’s three pillars of modern chemistry.](image1)

![Figure 2. The “converging stream” model for the protochemical period.](image2)
ern chemistry, via the table introduced in Lecture I, can pro-
vide the necessary basis for subdividing this 220-year span into
significant conceptual periods. In other words, I am of the
opinion, as the not-too-subtle title of this lecture has already
revealed, that modern chemistry has experienced, not just one,
but three distinct chemical revolutions, each of which corre-
sponds to one of the three conceptual levels—molar, molecu-
lar, and electrical—outlined earlier in our logic diagram. 2

The First Chemical Revolution: 1770–1790

The first of these, which initiated our current molar or
level-1 view of chemistry, is, of course, the famous revolu-
tion of Lavoisier. This roughly spans the period between
1772, when Lavoisier became interested in the role of gases
in chemical reactions, and 1789, when he published his fa-
mous Traité élémentaire de chimie (10). For convenience I have
rounded this off to the 20-year period from 1770 to 1790.
Though the confrontations in the chemical literature of the
period centered around the phenomenon of combustion and
an explicit attack on the theory of phlogiston, historians have
gradually come to realize that the conceptual foundations and
consequences of this revolution are far more complex than
this simple scenario would suggest. In particular, historian
Robert Siegfried has repeatedly argued that the true signi-
ficance of Lavoisier’s work lies in its general implications for
the concept of chemical composition at the molar level rather
than in just its specific revision of our models of combus-
tion and respiration (11).

I have attempted to summarize some of the factors that
contributed to the first chemical revolution in Figure 3. These
include new chemical theories of combustion and respiration,
developed by Mayow and other mechanical physiolo-
gists at Oxford in the late 17th century; the pneumatic
chemistry of Hales, Cavendish, Scheele, and Priestley, which led
to the discovery of new gases in the 1760s; the attempts to
refrain chemical nomenclature and classification on the ba-
sis of empirical composition, made by such chemists as
Macquer, Bergman, and Guyton in the 1760s and 1770s;
the development of the caloric theory of states by Black,
Crawford, Irving, Cleghorn, Watt, and Lavoisier; the exper-
imental defense of new theories of alkalinity and causticity
by Black and others, which explicitly acknowledged the role
of gases in chemical reactions and made use of conservation
of mass as a way of monitoring their absorption and evolu-
tion; and, lastly, various theories of calcination, including
those of Rey and, of course, the infamous phlogiston theory
of Becker and Stahl.

It should also be noted that Lavoisier’s work was not the
final word on the subject of molar composition and that the
formal theoretical structure for this level of chemical discourse
was actually completed by Josiah Willard Gibbs in 1875 with
the publication of his famous phase law.

The Second Chemical Revolution: 1855–1875

Unlike the first revolution, the second chemical revolu-
tion, which initiated access to the molecular or level-2 view
of chemistry, was not primarily due to just one person but
to an entire cluster of chemists who made contributions to
the emerging concepts of valence, molecular structure, and
the successful resolution of the problem of determining
atomic and molecular weights (12). It roughly spans the pe-
riod between 1852, when Edward Frankland imperfectly rec-
ognized the concept of valence, and 1874, when Jacobus van
Hoff postulated the tetrahedral carbon atom. For convenience
I have rounded this off to the 20-year period from 1855 to
1875. One of the important products of this revolution was
the replacement of earlier acid–base or dualistic classifica-
tions of elements with valence classifications, culminating in
the discovery of the periodic law by Mendeleev and others in the
1860s.

Again, I have attempted to summarize the important fac-
ctors contributing to this second chemical revolution by means
of the diagram in Figure 4. The first seeds of this revolution
were planted by Dalton in 1808 when he showed how the
concept of atomic weight could serve as a bridge connecting
the speculative atomism of the 17th century with the gravimeti-
cal analytical data that had resulted from the 18th-cen-
tury molar revolution. However, Dalton’s rules for assigning
formulas proved to be operationally flawed and, instead of
ushering in a new era of chemistry, they in fact ushered in a
half century of confusion (13). These decades also saw vari-
ous attempts to unravel the mysteries of organic chemistry
based on competing speculations about the internal struc-
ture of molecules—these speculations, in turn, being based
on various competing empirical and molecular formulas,
which, in turn, were based on various competing atomic and
so-called equivalent weight scales. This era, in my opinion,
is one of the most difficult for the modern chemist to un-
derstand. By the 1840s and 1850s, however, a sufficiently
large number of organic compounds and reactions had been
discovered so that, largely on the basis of simplicity and con-
istency arguments, such chemists as Laurent and Gerhardt
would opt for the use of what is essentially our modern atomic
weight scale, at least for the case of the common elements
found in organic compounds.

The key role, however, was played by the Italian chem-
ist Stanislao Cannizzaro, when he cracked the 50-year old
problem of determining a self-consistent set of atomic weights
in 1858. Though he showed that his conclusions were consistent with the more limited results obtained by Gerhardt, on the basis of organic taxonomy, and with those suggested much earlier by Avogadro, on the basis of gas densities, and by Petit and Dulong, on the basis of specific heats, it is incorrect to describe his contribution as a mere revival of earlier, overlooked, solutions to Dalton's dilemma. In fact, Cannizzaro's approach was based on a totally new and original method that combined gravimetric compositional data and gas density data for both simple substances and compounds. The resulting procedure was completely general and eliminated the ambiguities and operational limitations that had plagued previous suggestions (14).

**The Third Chemical Revolution: 1904–1924**

Unlike the first and second revolutions, which were largely internal to chemistry, the third chemical revolution, which initiated access to the electrical or level-3 view of chemistry, not only involved many participants but was shared with the discipline of physics. For chemistry, at least, it roughly spans the period between 1904, when Richard Abegg first suggested a correlation between the periodic table and valence-electron counts, and 1923, when Gilbert Newton Lewis published his classic monograph on *Valence and the Structure of Atoms and Molecules* (15). For convenience I have rounded this off to the 20-year period from 1904–1924.

The well-known revolutions in physics connected with the development of relativity theory and quantum mechanics are really episodes within this much larger development of an “electrical world view”, which replaced the mechanical world view that had dominated Western science since the early 17th century. Though the newer quantum mechanics certainly had implications for chemistry, the compositional and structural aspects of the electrical revolution, which had already emerged in the two decades before the advent of matrix mechanics in 1925 and wave mechanics in 1926, had far more impact for the average chemist.

As in the case of the previous two revolutions, I have attempted to summarize the various factors contributing to the third chemical revolution by means of the diagram in Figure 5. Here, however, we encounter an interesting pedagogical irony. Most modern chemistry textbooks include brief discussions of how each of these factors contributed to our understanding of the electrical structure of matter, with the exception of the two that are most explicitly chemical in nature—namely the periodic table and electrochemistry. Though even the most superficial acquaintance with the literature of this period shows that both of these topics played key roles in the development of the modern electronic theory of valence, they are instead presented in the textbook as deductions from—rather than as contributors to—the modern electrical theory of matter, which, in turn, is attributed solely to the work of physicists. In fact, not only did chemists make significant contributions to this theory via electrochemistry and the development of the periodic law, they made significant contributions, in the person of Sir William Crookes, to the study of gaseous discharge tubes, and they virtually dominated the study of radioactivity until the 1920s. After all, we need only remind ourselves that Rutherford was given, much to his chagrin, the Nobel Prize in chemistry, rather than physics, for his work on the disintegration theory of radioactivity. But here the irony often degenerates into farce, since the few textbooks that explicitly refer to Crookes by name, or to such radiochemists as Frederick Soddy or Otto Hahn, almost invariably misidentify them as physicists.

The net result of these suggestions is shown in Figure 6, which shows a revised and expanded version of the arrow head in our earlier “converging stream model”, and which explicitly incorporates our three modern chemical revolutions.

**Varieties of Scientific Revolution?**

Such a multiplication of revolutions requires that we pause and address the question of exactly what we mean when we speak of a “scientific revolution”. This is a problem on which historians of science have expended a great deal of paper and ink without having reached any general consensus (16). Without claiming any great originality, I would like to suggest that there are at least three acceptable answers:

1. A radical reinterpretation of existing thought.
2. The resolution of a long-standing debate, the solution of which revolutionizes the kinds of problems scientists are able to successfully attack on a routine basis.
3. The opening of a new level of theoretical understanding that subsumes older theories as special cases.

![Figure 5. Factors contributing to the third chemical revolution.](image)

![Figure 6. An expanded view of the tip of the arrow in Figure 2 incorporating the three-revolution model of modern chemistry.](image)
Most philosophers of science, using theoretical physics as their model, and pointing to the fact that Newtonian mechanics is a special limiting case of both relativity theory and quantum mechanics, have taken answer 3 as their definition of a scientific revolution (17). I, on the other hand, would argue that only the third chemical revolution fits this description. Lavoisier’s oxygen theory did not subsume the phlogiston theory as a special case. In fact, it literally turned the phlogiston theory inside out by substituting “plus oxygen” for “minus phlogiston” in virtually every known chemical process. Likewise, though the theory of combustion became the focus for the confrontation between Lavoisier’s system and the phlogiston theory, historians have shown that it was not a long-standing problem in chemistry that previous generations of chemists had been unsuccessfully trying to solve. In short, answer 1 is the best characterization of the first chemical revolution.

By way of contrast, Cannizzaro’s solution to the atomic weight problem did not subsume any earlier theories as special cases nor did it produce any radical reinterpretation of existing fact. Rather it allowed chemists to operationally choose from among several competing speculative views of molecular composition and structure and so resolved a long-standing debate. In other words, answer 2 is the best characterization of the second chemical revolution.

In broader terms, what I am suggesting is that the history of chemistry provides us with a much more general view of the nature of scientific change than does the history of theoretical physics and consequently with a much richer selection of examples for use in the classroom.

At this juncture I should also confess that I am personally of the opinion that all scientific change is really evolutionary rather than revolutionary in the strict sense of the word. By revolution I am really referring to a period of time in which there is a rapid development and convergence of already existing streams of thought, many of which already have long histories. The somewhat arbitrary 20-year spans I have used to characterize each chemical revolution are intended merely to represent such periods of rapid development and consolidation. In each case there is a prehistory and a subsequent period of refinement. Elsewhere I have expressed this by characterizing revolutions of thought as “the art of making explicit the implicit,” though the British chemist and historian J. C. Gregory said it even better many years ago when he observed that (18, 19):

Revolutions in thought are usually steady maturations suddenly completed.

As anyone who frequents the science sections of Borders Books or of Barnes and Noble knows, the phrase “scientific revolution” has become a modern buzz word for anyone trying to market their particular area of research. The shelves of these sections abound with books hyping self-proclaimed scientific revolutions on behalf of information theory, systems theory, chaos theory, fractal theory, catastrophe theory, and irreversible thermodynamics. Is there some set of criteria for sorting the real from the self-appointed, be they the brain-children of the present or the past? In short, what kinds of evidence can we use to support our contention that each of the above periods corresponds to a significant chemical revolution? Again, without making any claims to great originality, I would like to suggest that there are at least four things we can look for:

1. Widespread and persistent contemporary accounts that make explicit claims that a scientific revolution is in the making. (Put another way, hype is a necessary but not a sufficient condition).
2. Significant and explicit changes in the content, vocabulary, and organization of textbooks before and after the period in question.
3. Significant changes in research emphasis and practice.
4. Significant changes in the structure of academic and professional organizations, including the founding of new academic chairs, new research institutes, new scientific societies, and new journals.

Of these, I would say that criterion 2 is by far the most significant, though ironically it is the one that has been least studied by historians. This may in part be a reflection of the ambiguous status of the textbook within science itself. As anyone who has spent time in a university knows, the writing of textbooks is considered to be one of the least prestigious forms of scientific output. Yet in the overall scheme of things it is also the most important, since, in the distillation of information from research article, to review article, to specialized monograph, to textbook, it represents the final refinement. It is the ultimate arbiter of what small fraction of the vast output of one generation is deemed worthy of being passed on to the next.

In light of these considerations, let us reconsider each of our three revolutions and attempt to briefly evaluate how well they stand up to some of these criteria.

The First Chemical Revolution: Molar Composition

It is hardly necessary to justify this revolution as it has long been accepted as such by historians. As far as criterion 1 is concerned, Lavoisier, together with both his supporters and opponents, explicitly stated on numerous occasions that nothing less than a revolution in chemical thought was at stake in the confrontation between the oxygen and phlogiston theories (20). Lavoisier used the term “revolution” in his private notebooks, and in 1788 Fourcroy added a long section to the third edition of his text Éléments d’histoire naturelle et de chimie entitled “A Discourse on Modern Chemistry”—with the emphasis on the term “modern”—in which he summarized Lavoisier’s system (21).

To the best of my knowledge, no one has done a study based on the application of criterion 2, though such a project would be of great interest. A preliminary survey of textbooks from this period suggests that both Lavoisier’s own Traité and especially the 3rd edition of Fourcroy’s Éléments, just mentioned, provided the prototypes for a new generation of textbooks based on the new “antiphlogistic” chemistry (22). Due to the accompanying nomenclature reforms introduced by Lavoisier, Guyton de Morveau, Fourcroy and Berthollet, there is little problem in differentiating between pre- and post-revolutionary texts.

An example of the application of criterion 3 is shown in the bar graph in Figure 7, which is based on the data collected by McCann, and which clearly shows the progressive change in the percentage of papers in the French chemical literature making use of the phlogiston versus the oxygen theory (23).

As for criterion 4, the most obvious example involves the founding in 1789 of the new journal Annales de chimie et de physique by Lavoisier and his collaborators.
The Second Chemical Revolution: Molecular Composition/Structure

Again, chemists of the period explicitly recognized that something significant had happened and reflected this in the titles of the books they wrote, which repeatedly made use of the operative adjectives "new" and "modern." The earliest and most scholarly of these is the monograph, Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik (Modern Theories of Chemistry and their Significance for Chemical Statics), by the German chemist Lothar Meyer (24). First published in 1864, it underwent numerous editions, revisions, and translations until the end of the century, and remained the most authoritative book on theoretical chemistry until its displacement by Wilhelm Ostwald’s famous Lehrbuch der allgemeinen Chemie in the 1890s.

In England, the revolution was announced the very next year (1865) by the publication of August Wilhelm Hofmann’s equally famous text, Introduction to Modern Chemistry. Based on his introductory lectures at the Royal College of Chemistry in London, Hofmann’s book lacked the scholarly apparatus of Meyer’s, but is a true masterpiece of chemical pedagogy, and one which, in my opinion, should be read by every serious teacher of chemistry. Lest there be any doubts as to what Hofmann meant to imply by his use of the term “modern” in his title, one needs only to turn to the introduction (25):

No chemist will need to be reminded that, during the last quarter of a century, the science of chemistry has undergone a profound transformation; attended, during its accomplishment, by struggles so convulsive, as to represent what, in political parlance, would be appropriately termed a Revolution.

In France, the history of the new revolution was described by Adolphe Wurtz in 1869 in his monograph, Histoire des doctrines chimiques depuis Lavoisier jusqu’a nos jours (A History of Chemical Theory from the Age of Lavoisier to the Present) (26). A popular and highly readable account of the events that had so recently transformed chemistry, the book was translated into English the same year by Henry Watts. However, concern that this new revolution would be misinterpreted by French chemists as an attempt to destroy the work of Lavoisier, and so diminish the glory of France, caused Wurtz to make some rather problematic claims in his efforts to demonstrate that, not only had French chemists played a significant role in this revolution (including Wurtz himself), but that the revolution had, in effect, extended and generalized Lavoisier’s work rather than undermined it. In particular, these nationalistic concerns tempted Wurtz into making his famous, or rather infamous, remark in the opening sentence of the book that (27):

Chemistry is a French science. It was founded by Lavoisier, of immortal memory.

In the United States, Josiah Parsons Cooke of Harvard University proclaimed the revolution in a series of popular lectures given at the Lowell Institute in Boston in 1872 and published two years later under the title of The New Chemistry. As with Hofmann, Cooke’s introduction leaves no doubt about just what the adjective “new” was intended to imply (28):

These lectures aimed to present the modern theories of chemistry to an intelligent but not a professional audience, and to give the philosophy of the science a logical consistency, by restating it on the law of Avogadro. Since many of the audience had studied chemistry under the dualistic system, it was also made an object to point out the chief characteristics by which the new chemistry differed from the old.

Though the 1874 date for Cooke’s book might seem to indicate that the Americans were, as usual, lagging behind their European colleagues, in fact several American textbooks based on the new chemistry had already appeared by the time Cooke’s popularization saw the light of day. These included both Cooke’s own superb text, First Principles of Chemical Philosophy, published in 1868 (29), and George F. Barker’s Textbook of College Chemistry, which appeared in 1870. Barker, who was Professor of Chemistry at Yale, and later Professor of Physics at the University of Pennsylvania, was quite explicit about the need for a new textbook, since, as he wrote in the introduction (30):

...within the past ten years, chemical science has undergone a remarkable revolution ...

Norr was there any ambiguity in Barker’s mind as to the exact nature of this revolution (30):

The changes which have so entirely altered the aspect of the science, however, are not, as some seem to suppose, changes merely in the names and formulas of chemical compounds … They are changes which have had their origin in the discovery, first, that each element has a fixed and definite combining power or equivalence; and second, that in a chemical compound, the arrangement of the atoms is of quite as much importance as their kind or number … The importance of these laws cannot be overestimated. By the former, all the compounds formed by any element may be with certainty predicted; by the latter, all the modes of atomic grouping may be foreseen, and the possible isomers of any substance be predetermined. Instead, therefore, of being a heterogeneous collection of facts, chemistry has now become a true science, based upon a sound philosophy [italics added].

In other words, the revolution rested not only upon self-consistent atomic and molecular weights, as Cooke had emphasized, but upon the concepts of valence (definite combining power) and molecular structure (arrangement of atoms).

The same effect can also be seen in the new editions of books originally written prior to this period. Thus the 1875

---

Figure 7. The percentage of the French chemical literature dealing with the phlogiston versus the oxygen theory as a function of time.
The percentage by decade of American chemistry textbooks using affinity theory versus valence as an organizational principle.

For this is that, of the three chemical revolutions, the second is the one that seems to have been most consistently overlooked by previous chemical historians. This claim might seem incredible, given that even the most superficial examination of the textbooks of the period yields, as we have just seen, an overabundance of explicit statements in support of this interpretation. However, you must bear in mind that professional historians and chemists are seldom interested in textbooks.

More recently, however, an increasing number of younger chemical historians have come to accept this point of view. Thus historian J. A. Johnson, in a detailed study of changes in the power structure of German chemistry in the period 1871–1914, has assembled an impressive array of social and institutional evidence (corresponding to criterion 4) in support of both a second and a third chemical revolution, which he independently identifies with the same time periods that we have selected on the basis of our logic table and the use of criteria 1–3 (34). Likewise, American historian Alan Rocke has repeatedly used the phrase “quiet revolution” to characterize the changes that occurred in chemistry midway through the 19th century (35). However, he identifies these with specific changes in the practice of organic chemistry in the 1850s, whereas I feel that the resulting taxonomic reform of organic chemistry is but one of several factors contributing to the second revolution and that this revolution was not completed until the advent of the periodic law in 1869 and the tetrahedral carbon atom in 1874.

The Third Chemical Revolution: Electrical Composition/Structure

As before, these changes were explicitly recognized at the time as constituting a major revolution and this view was reflected in the titles of scores of popular books and articles. A far from exhaustive list is given in Table 1. Again note the preponderance of the word “new” in the titles. Also note that four of these books appeared before the publication of the Bohr atom in 1913 and all of them before the development of modern quantum mechanics in the period 1925–1926.

Likewise, we again have explicit statements from the participants that something revolutionary had happened. Thus, on updating his original 1902 article on “Chemistry” for the 1921 supplement to the Encyclopaedia Britannica, the British
chemist, Henry Armstrong, observed (36):
Subsequent progress [since 1902] has been astounding,
so much so that chemistry appears, during 1905–1920,
to have entered upon yet another era. New methods have
been introduced and a degree of certainty has been given
to the primary postulates of the science which, even
within living memory, could not have been contemplated
as within the bounds of attainment; at the same time,
old suspicions have been justified and conceptions which
had long been entertained have been realized. The ad-
vance is mainly the outcome of studies on the border-
land region between chemistry and physics and is due to
much overlapping of inquiry.

Without a doubt the “Traité” for this revolution, for chem-
ists at least, would be G. N. Lewis’ monograph on Valence
and the Structure of Atoms and Molecules mentioned earlier.

Finally, as an example of the founding of new journals,
cited in criterion 4, we might take the case of the Jahrbuch
der Radioaktivität und Elektronik. Begun in 1904 as a review
journal for the new fields of radioactivity and the electrical
theory of matter, its editorial board reflected the coequal roles
played by both chemists and physicists in initiating this rev-
olution, and included such luminaries as Svante Arrhenius,
Pierre and Marie Curie, Ernest Rutherford, Frederick Soddy,
and Johannes Stark.

Other Analogies

So far, in our discussions of both the pedagogical and his-
torical implications of our logic chart, we have focused exclu-
sively on the three levels of discourse. In closing, I would like to
briefly indicate how a similar focus on the three dimensions of
our chart can lead to a number of additional historical insights.
For example, the much greater importance that the average
chemist attaches to the composition/structure dimension ver-
sus the energy dimension and the time dimension is reflected in
the different relative rates of historical development for these
dimensions, in the case with which students assimilate them,
and in the percentage of space devoted to them in both current
introductory texts and in histories of chemistry. An interesting
historical analysis of the gradual introduction of the time di-
imension into chemistry was made by Tód Benfey many years
ago using a viewpoint closely related to that given here (37).

Likewise, a quick survey of 12 of the more recent general
histories of chemistry showed that less than 2% of the text ma-
terial was devoted to the history of affinity theory, chemical ther-
modynamics, and chemical kinetics. Even then, the few exist-
ing references that were included usually had to do with topics
that had a significant overlap with the composition/structure
dimension, such as the manner in which Berthollet’s theory of
mass action influenced his views on the law of definite compo-
sition. Indeed, from a broader perspective, it is worth noting
that, prior to the introduction of the conservation of energy con-
cept in the 1840s by Mayer, Joule, Helmholtz and others, chem-
ists attempted, via the use of the caloric theory and asserted im-
ponderable electrical and magnetic fluids, to collapse the energy
dimension into the composition/structure dimension by view-
ing exo- and endoenergetic changes as single-displacement re-
actions involving the release or uptake of definite quantities of
chemically combined imponderable fluids (38).

Similarly, the major factor that distinguishes the so-called
new “physical chemistry”, advocated by Ostwald, van’t Hoff,
and Arrhenius in the 1890s, from the older “theoretical chem-
istry” found in the treatises written by Kopp, Meyer, and
Remsen in the period between 1857 and 1877, is that the
latter focused almost exclusively on problems related to mo-
lecular composition and structure, whereas Ostwald in-
isted on the importance of studying the energy and time
dimensions of chemistry as well (39). His attempts to char-
acterize physical chemistry as an independent subdiscipline
eventually led Ostwald to question the scientific validity of
the atomic–molecular theory and to an attempt to reconstruct
chemistry using only the molar level of discourse. The best
summary of his alternative molar chemistry is his 1904 Far-
day lecture on “Elements and Compounds”, which was fol-
lowed in 1907 by a 540-page monograph entitled Prinzipien
der Chemie: Eine Einleitung in alle chemischen Lehrbücher (40,
41). By the next year, however, Ostwald had recanted, and
in 1908, in the introduction to the third edition of his text,
Outlines of General Chemistry, he wrote (42):

I am now convinced that we have recently become pos-
sessed of experimental evidence of the discrete or grained
nature of matter, which the atomic hypothesis sought in
vain for hundreds and thousands of years. The isolation
and counting of gas ions, on the one hand, which have
crowned with success the long and brilliant researches of
J. J. Thomson, and, on the other, the agreement of the
Brownian movements with the requirements of the ki-
netic hypothesis established by many investigators and
most conclusively by J. Perrin, justify the most cautious
scientist in now speaking of the experimental proof of
the atomic nature of matter. The atomic hypothesis is
thus raised to the position of a scientifically well-founded
theory, and can claim its place in the textbook intended
as an introduction to the present state of our knowledge
of general chemistry.

It is not without significance that, of the two pieces of
experimental evidence cited by Ostwald, one dealt with the
electrical level of discourse and the other with the molecular
level.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1905</td>
<td>Sachur</td>
<td>On the Meaning of the Electron Theory for Chemistry</td>
</tr>
<tr>
<td>1906</td>
<td>Jones</td>
<td>The Electrical Nature of Matter and Radioactivity</td>
</tr>
<tr>
<td>1910</td>
<td>Tunzelmann</td>
<td>A Treatise on Electrical Theory and the Problem of the Universe</td>
</tr>
<tr>
<td>1914</td>
<td>Letts</td>
<td>Some Fundamental Problems of Chemistry: Old and New</td>
</tr>
<tr>
<td>1919</td>
<td>Comstock &amp; Troland</td>
<td>The Nature of Matter and Electricity</td>
</tr>
</tbody>
</table>
Notes

1. Perceptive readers may have noticed the absence of any mention of either Chinese or Indian alchemy. This is because archaeology and scholarship have so far failed to establish a definite link between them and western alchemy. If such a link does exist, it probably occurred during the Islamic period, as tentatively indicated in Figure 2.

2. The three-revolution model of the history of chemistry outlined in this lecture was first presented in July of 1991 as part of a Summer Workshop in the History of Chemistry sponsored by the Beckman Center for the History of Chemistry in Philadelphia.

Literature Cited

5. Bergman, T. Of the Origin of Chemistry. In Essays, Physical and Chemical Mudie & Fairbairn: Edinburgh, 1791; p. 4. Weyer (4) claims that this essay was actually written by a student of Bergman by the name of Jacob Paulin.
6. Fourcroy, A. F. Elements of Chemistry and Natural History, 4th ed.; Mudie & Cuthell: Edinburgh, 1796; Chapter 2. I have paraphrased Fourcroy's rather lengthy descriptors of each period.
9. Ihde, A. J. The Development of Modern Chemistry; Harper & Row: New York, NY, 1962. This is currently available as a quality Dover paperback reprint. The statement about current coverage should be qualified relative to the recent history by Brock (Brock, W. H. The Norton History of Chemistry; Norton: New York, NY, 1993) which, though less thorough than Ihde, does attempt to selectively cover more recent events, such as the early development of the electronic theory of organic reactivity.
12. Though there is no general history of the second chemical revolution as such, the valence aspect is well treated in Russell, C. A. The History of Valency; Leicester University Press: Leicester, 1961.
15. There is no general history of the electrical revolution. However, many of the more important chemical aspects are covered in Stranges, A. N. Electrons and Valence, Development of the Theory, 1900–1925 Texas A&M: College Station, TX, 1982. A delightfully readable account from the standpoint of the physicist can be found in Keller, A. The Infancy of Atomic Physics: Hercules in his Cradle; Clareendon Press: Oxford, 1983.
17. This third interpretation of a scientific revolution has been dubbed the "generalized correspondence principle" in Sachs, M. Einstein versus Bohr: The Continuing Controversies in Physics; Open Court: La Salle, IL, 1988: p 13.
39. See Kopp, H. Theoretische Chemie und Beziehungen zwischen chemischen und physikalischen Eigenschaften; Vieweg: Braunschweig, 1857 (This forms Part II of Volume 1 of Graham-Orts’s Aufführliches Lehrbuch der Chemie); and Remsen, J. Principles of Theoretical Chemistry with Special Reference to the Constitution of Chemical Compounds; Lea: Philadelphia, PA, 1877. For Meyer see reference 24.