

Report: New England Association of Chemistry Teachers

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, *Lecons 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 pharmaceutical, philosophical and pneumatic periods (7):

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

Further Modifications of the Protochemical Era

With few exceptions, most 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 Hellenistic, 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.¹

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 (8).

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 Fourcroy, 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 phlogiston 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 Chymist*—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 (9).

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-

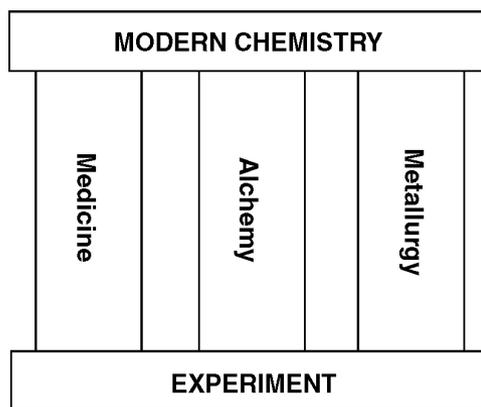


Figure 1. Ihde's three pillars of modern chemistry.

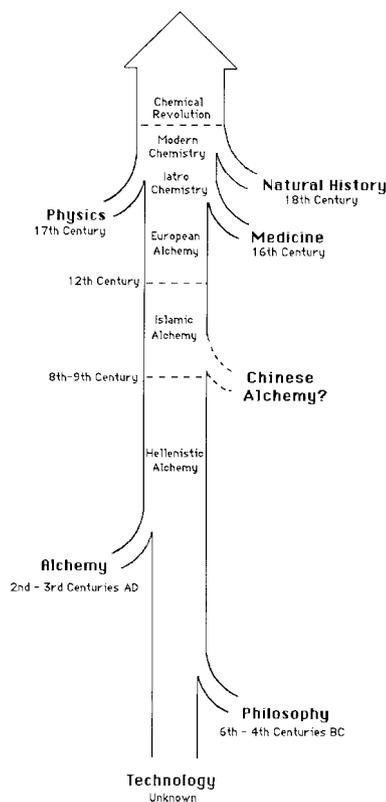


Figure 2. The "converging stream" model for the protochemical period.

ern chemistry, via the table introduced in Lecture I, can provide 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 corresponds to one of the three conceptual levels—molar, molecular, 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 revolution 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 famous *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 significance 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 combustion 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 physiologists 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 reform chemical nomenclature and classification on the basis 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 experimental 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 evolution; 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

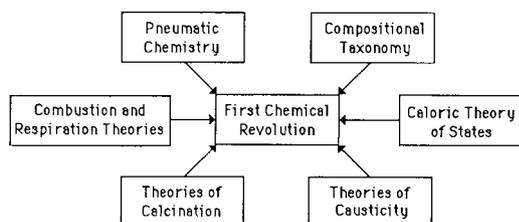


Figure 3. Factors contributing to the first chemical revolution.

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 revolution, 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 period between 1852, when Edward Frankland imperfectly recognized the concept of valence, and 1874, when Jacobus van't 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 classifications 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 factors 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 gravimetric analytical data that had resulted from the 18th-century 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 various attempts to unravel the mysteries of organic chemistry based on competing speculations about the internal structure 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 understand. 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 consistency 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 chemist Stanislao Cannizzaro, when he cracked the 50-year old problem of determining a self-consistent set of atomic weights

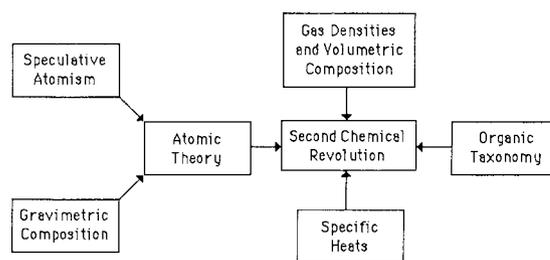


Figure 4. Factors contributing to the second chemical revolution.

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 radioactiv-

ity. 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.

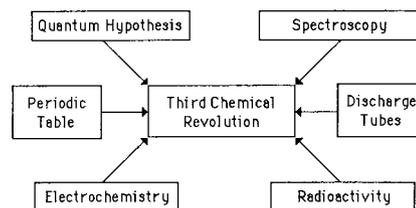


Figure 5. Factors contributing to the third chemical revolution.

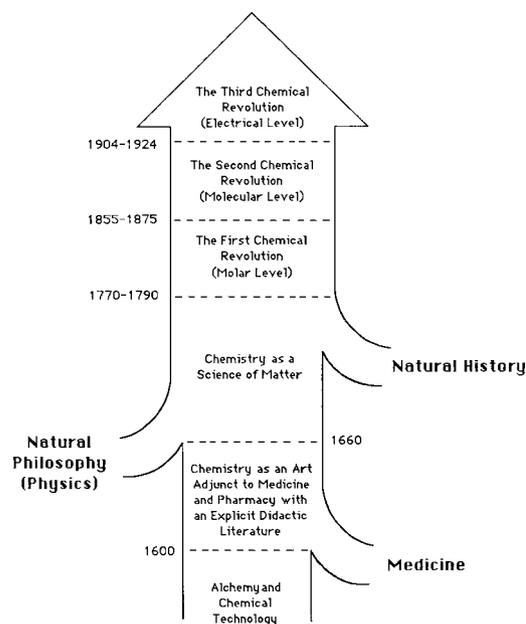


Figure 6. An expanded view of the tip of the arrow in Figure 2 incorporating the three-revolution model of modern chemistry.

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-annointed, 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.

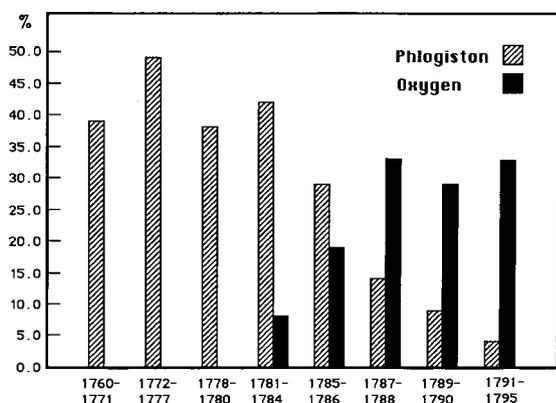


Figure 7. The percentage of the French chemical literature dealing with the phlogiston versus the oxygen theory as a function of time.

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'à 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 resting 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 ...

Nor 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

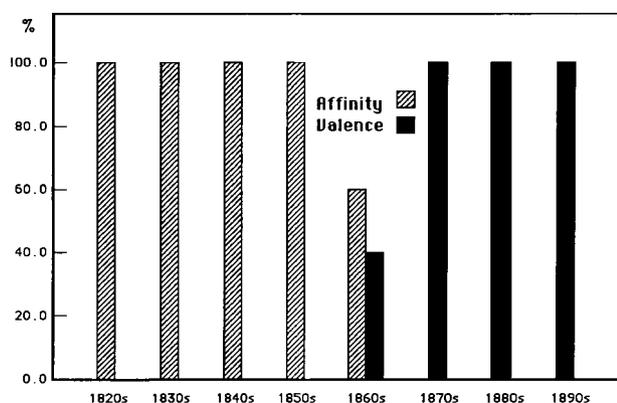


Figure 8. The percentage by decade of American chemistry textbooks using affinity theory versus valence as an organizational principle.

edition of Edward L. Youmans' original 1852 text, *A Class-Book of Chemistry*, carried the additional subtitle, *On the Basis of the New System*, and a word of explanation to the readers in the introduction that (31):

These modifications have been long in progress and having at length issued in a new system of chemical doctrine, which has generally been accepted by chemists, it has been adopted in the present volume.

Likewise, the 1875 edition of Carl Remigius Fresenius' original 1848 text, *Manual of Qualitative Chemical Analysis*, now carried the additional subtitle, *Translated into the "New System"*, as did the later editions of his *Outlines of Quantitative Analysis*, and the editorial comment that (32):

In form the book is quite changed by the use throughout of the language and notation of "modern chemistry"; a change called for by the universal adoption of the "New System", as well as by its inherent advantages.

The fact that similar statements and titles did not appear after the publication of Dalton's original work on the atomic theory earlier in the century is consistent with the idea that he is the precursor rather than the perpetrator of this revolution.

The before and after effect on textbook organization, required by criterion 2, can be clearly seen in the bar graph in Figure 8, which shows the percentage of introductory American and British textbooks by decade organized around affinity laws versus those making use of valence concepts. The use of the so-called laws of chemical affinity as an organizational framework dates back to Fourcroy. Interestingly, the change to an emphasis on valence and molecular structure is so sharply defined, that after 1870 the term "affinity" can no longer be found in the indices of most textbooks.

Finally, an example of the impact on research practice (criterion 3) can be seen in the bar graph in Figure 9, which shows the data collected by Robert Siegfried on the percentage of papers by decade published in the American chemical literature that deal with mineral analysis versus organic chemistry (33). The switch from the dominance of inorganic and analytical research to the dominance of organic research, which accompanied the introduction of structure theory in the 1860s, is clearly evident.

I must apologize for having spent so much time presenting evidence for the second chemical revolution. The reason

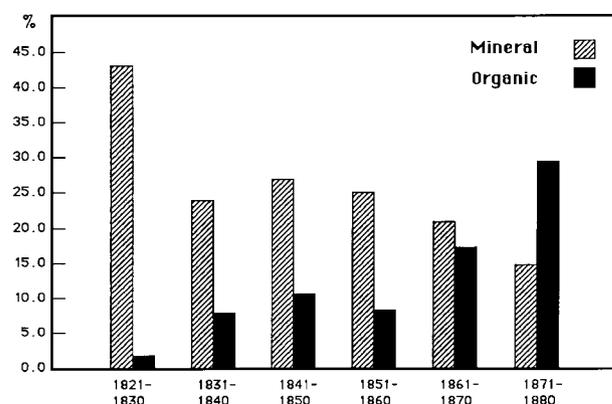


Figure 9. The percentage by decade of the American chemical literature dealing with mineral analysis and inorganic chemistry versus organic chemistry.

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 *Encyclopædia 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 advance is mainly the outcome of studies on the borderland region between chemistry and physics and is due to much overlapping of inquiry.

Without a doubt the “*Traité*” for this revolution, for chemists 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 revolution, 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 historical implications of our logic chart, we have focused exclusively 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 versus the energy dimension and the time dimension is reflected in the different relative rates of historical development for these dimensions, in the ease 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 dimension into chemistry was made by Ted 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 material was devoted to the history of affinity theory, chemical thermodynamics, and chemical kinetics. Even then, the few existing 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 composition. Indeed, from a broader perspective, it is worth noting that, prior to the introduction of the conservation of energy concept in the 1840s by Mayer, Joule, Helmholtz and others, chemists attempted, via the use of the caloric theory and assorted imponderable electrical and magnetic fluids, to collapse the energy dimension into the composition/structure dimension by viewing exo- and endoenergetic changes as single-displacement reactions 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 chemistry” 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 molecular composition and structure, whereas Ostwald insisted on the importance of studying the energy and time dimensions of chemistry as well (39). His attempts to characterize 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 Faraday lecture on “Elements and Compounds”, which was followed 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 possessed 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 kinetic 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 1. Examples of Early Books Proclaiming the Third Chemical Revolution

Year	Author	Title
1905	Sachur	On the Meaning of the Electron Theory for Chemistry
1905	Duncan	The New Knowledge: A Simple Exposition of the New Physics and the New Chemistry in Relation to the New Theory of Matter
1906	Jones	The Electrical Nature of Matter and Radioactivity
1910	Tunzelmann	A Treatise on Electrical Theory and the Problem of the Universe
1914	Letts	Some Fundamental Problems of Chemistry: Old and New
1919	Comstock & Troland	The Nature of Matter and Electricity

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

- Jensen, W. B. Does Chemistry Have a Logical Structure? *J. Chem. Educ.* **1998**, *75*, 679–687; Can We Unmuddle the Chemistry Textbook? **1998**, *75*, 817–828.
- Popper, K. R. *The Poverty of Historicism*, Routledge & Kegan Paul: London, 1957.
- Candler, A. C. *Atomic Spectra and the Vector Model*, Cambridge University Press: Cambridge, 1937; Vol. I, p 2.
- Weyer, J. *Chemiegeschichtsschreibung von Wiegleb (1790) bis Partington (1970)*; Gerstenberg: Hildesheim, 1974.
- 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.
- 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.
- Kopp, H. *Geschichte der Chemie*, Vieweg: Braunschweig, 1843–1847; Vol. 1–4. Kopp uses this classification in volume 1.
- Ihde, A. J. The Pillars of Modern Chemistry. *J. Chem. Educ.* **1956**, *33*, 107–110.
- 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 the early development of the electronic theory of organic reactivity.
- The most detailed study of the origins of the first chemical revolution is still Guerlac, H. *Lavoisier - The Crucial Year*; Cornell University Press: Ithaca, NY, 1961. Some recent reassessments are given in *The Chemical Revolution, Essays in Reinterpretation*. Donovan, A., Ed.; *Osiris* **1988**, *4* (Spec. Issue); and *Lavoisier and the Chemical Revolution*. Miller J. A. and Jensen, W. B., Eds.; *Bulletin for the History of Chemistry* **1989**, No. 5 (Spec. Issue).
- Siegfried R. and Dobbs, B. J. Composition, A Neglected Aspect of the Chemical Revolution. *Ann. Sci.* **1968**, *24*, 275–293.
- 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.
- Bernatowicz, A. Dalton's Rule of Simplicity. *J. Chem. Educ.* **1970**, *47*, 577–579.
- The best assessment of Cannizzaro's work is still Nash, L. K. *The Atomic-Molecular Theory*; Harvard Case Histories in Experimental Science, Case 4; Harvard University Press: Cambridge, MA, 1964.
- 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*, Clarendon Press: Oxford, 1983.
- The most thorough treatment of the concept of scientific revolution is found in Cohen, I. B. *Revolution in Science*, Harvard University Press: Cambridge, MA, 1985. For an example of a revisionist approach which, in extreme cases, rejects the concept of revolution altogether, see *Reappraisals of the Scientific Revolution*, Lindberg, D. C. and Westman, R. S., Eds.; Cambridge University Press: Cambridge, 1990.
- 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.
- Jensen, W. B. Thomas Duché Mitchell and the Chemistry of Principles. *Bull. Hist. Chem.* **1989**, *5*, pp 42–48.
- Gregory, J. C. The Animate and Mechanical Models of Reality. *J. Phil. Stud.* **1927**, *2*, pp 301–314.
- Gough, J. C. Some Early References to Revolutions in Chemistry. *Ambix* **1982**, *29*, 106–109.
- Guerlac, H. The Chemical Revolution: A Word from Monsieur Fourcroy. *Ambix* **1976**, *23*, 1–4.
- For the influence of Fourcroy's text, see Chastain, B. B. Books of the Chemical Revolution II: *Éléments d'Histoire Naturelle et de Chimie*. *Bull. Hist. Chem.* **1989**, *4*, 8–11.
- McGann, H. G. *Chemistry Transformed: The Paradigmatic Shift from Phlogiston to Oxygen*; Ablex: Norwood, NJ, 1978; Chapter 4.
- Meyer, L. *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik*; Maruschke & Berendt: Breslau, 1864.
- Hofmann, A. W. *Introduction to Modern Chemistry, Experimental and Theoretic*; Walton & Maberley: London, 1865; p v.
- Wurtz, A. *Histoire des doctrines chimiques depuis Lavoisier jusqu'à nos jours*, Hachette: Paris, 1869; translated by Henry Watts as *A History of Chemical Theory from the Age of Lavoisier to the Present*, Macmillan: London, 1869.
- I owe this insight into Wurtz's motives to Rocke, A. J. Pride and Prejudice in Chemistry: Chauvinism and the Pursuit of Science. *Bull. Hist. Chem.* **1992–1993**, *13/14*, 29–40.
- Cooke, J. P. *The New Chemistry*, Appleton: New York, NY, 1874; p 5.
- Cooke, J. P. *First Principles of Chemical Philosophy*; Sever & Francis: Boston, 1868. In the case of Europe, early important textbook presentations of the new revolution include: Naquet, A. *Principles of Chemistry Founded on Modern Theories*; Renshaw: London, 1867 (1st ed., 1864); and Frankland, E. *Lecture Notes for Chemical Students*, Van Voorst: London, 1866.
- Barker, G. F. *A Textbook of College Chemistry*, Morton: Louisville, KY, 1870; p iii.
- Youmans, E. L. *A Class-Book of Chemistry On the Basis of the New System*, Appleton: New York, NY, 1875; p 3.
- Fresenius, C. R. *Manual of Qualitative Chemical Analysis: Translated into the "New System"*; 8th ed.; Wiley: New York, NY, 1875; p v.
- Siegfried, R. A Study of Chemical Research Publications from the United States Before 1880. Ph.D. Thesis, University of Wisconsin, Madison, WI, 1952, pp 96–97.
- Johnson, J. A. Hierarchy and Creativity in Chemistry, 1871–1914. *Osiris* **1989**, *5*, 214–240.
- Rocke, A. J. *The Quiet Revolution: Hermann Kolbe and the Science of Organic Chemistry*; University of California: Berkeley, CA, 1993.
- Armstrong, H. Chemistry. In *The Encyclopædia Britannica, The New Volumes* The Encyclopædia Britannica Co: London, 1922; Vol. 30, p 621.
- Benfey, O. T. Concepts of Time in Chemistry. *J. Chem. Educ.* **1963**, *40*, 574–577.
- Dyke, D. R. The Nature of Heat and its Relationship to Chemistry in the Eighteenth Century. Ph.D. Thesis, University of Wisconsin, Madison, WI, 1967.
- See Kopp, H. *Theoretische Chemie und Beziehungen zwischen chemischen und physikalischen Eigenschaften*, Vieweg: Braunschweig, 1857 (This forms Part II of Volume 1 of Graham-Otto's *Auführliches Lehrbuch der Chemie*); and Remsen, I. *Principles of Theoretical Chemistry with Special Reference to the Constitution of Chemical Compounds*, Lea: Philadelphia, PA, 1877. For Meyer see reference 24.
- Ostwald, W. Elements and Compounds. *J. Chem. Soc.* **1904**, *85*, 506–522.
- Ostwald, W. *Prinzipien der Chemie: Eine Einleitung in alle chemischen Lehrbücher*; Akademische Verlagsgesellschaft: Leipzig, 1907, translated by Harry W. Morse as *The Fundamental Principles of Chemistry: An Introduction to All Text-Books of Chemistry*, Longmans, Green & Co: London, 1909.
- Ostwald, W. *Outlines of General Chemistry*, 3rd ed.; Macmillan: London, 1912; p vi.