Logic, History and the Chemistry Textbook:

A Reappraisal and Update

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1. Introduction

In 1998 I published a three-part article in the *Journal of Chemical Education* under the general title of "Logic, History and the Chemistry Textbook," based on a series of lectures which I had given in 1995 to the 57th Conference of the New England Association of Chemistry Teachers (1-3). These were a summary of my search over the previous decade for a more logical and unified way of presenting the fundamental ideas and concepts of modern chemistry to introductory students and were born of my personal frustration, starting in graduate school, with what I perceived as the largely random and unintegrated presentation of chemistry I had been subject to in the course of my own chemical training, as well as the frustration of my own students at Cincinnati, who, though largely unable to articulate the source of their almost universal dislike of chemistry, seemed to also be responding negatively to the random topics approach found in the typical chemistry textbook.

The precise nature and origins of this frustration were somewhat bleakly summarized by me in a departmental seminar on chemical education which I had given shortly after coming to Cincinnati (4):

Freshman chemistry is the garbage heap of the chemistry curriculum. It is composed of the cumulative dregs of those topics that instructors in more advanced courses no longer wish to teach and consists largely of the random presentation of terminology generated by highly approximate theoretical models the student never fully understands and which were originally designed to rationalize limited ranges of experimental facts that, since the demise of descriptive chemistry, the student is no longer taught.

The key to my own attempts to rectify this situation ultimately came from my study of the history of chemistry and, unbeknownst to me at the time, were a vindication of a claim made almost a century earlier by the German chemist and chemical historian, Albert Ladenburg (figure 1), in his well-known lectures on the history of chemistry (5):

Figure 1. Albert Ladenburg (1842-1911).

A retrospect of the past, especially in the exact sciences, alone affords a proper comprehension of what is accepted today. It is only when we are acquainted with the theories which preceded those accepted at present, that the latter can be fully understood; because there is almost always an intimate connection between them.

Indeed, since publishing the original lectures, I have continued to apply Ladenburg's credo, though on a less ambitious scale, through my historical question and answer column in the *Journal of Chemical Education*. Responding to the questions about the origins of nomenclature, symbolism, definitions and laboratory techniques sent in by chemistry teachers throughout the world has proven both challenging and educational, though probably more so for myself than for my readers. And it can also occasionally be disillusioning – especially when one discovers that a concept or a particular terminology is not the infallible God-given truth your colleagues believe it to be but rather an historical

accident or convention due perhaps to a failure to properly eliminate outdated vocabulary (e.g. oxidation-reduction terminology), the accidental choice of a particular instrumental procedure (e.g. the electrometric measurement of H^+ concentration and the pH concept), or the parochialization of a once general concept as a result of sloppy usage and narrow specialization (e.g. the polymer concept).

As shown in figure 2, in Part I of my original lecture series I attempted to group the basic concepts of chemistry into nine categories depending on whether they dealt with the composition/structure, the energy, or the time dimensions of chemical phenomena, and on whether they were formulated at the molar, molecular or electrical levels of chemical discourse (1). In Part II, I illustrated how these distinctions could be used to clarify the accepted textbook treatments of certain subjects (2), and finally, in Part III, I illustrated how this classification was reflected in the historical evolution of chemistry itself, and especially in how our three current levels of chemical discourse corresponded to three distinct chemical revolutions: the molar level to the classical revolution of Lavoisier and his collaborators in the period 1770-1790; the molecular level to the revolution connected with the emergence of the concepts of classical structure theory and the kinetic theory of matter in the period 1855-1875, and the electrical level with the emergence of the electronic theory of bonding and reactivity in the period 1904-1924 (3).

Fifteen years have now elapsed since I first articulated these ideas and, for at least a decade, I was given an opportunity to implement many of them in the classroom. What I propose to do today is to summarize this classroom experience with you in terms of how I had to modify and amplify some of my original ideas and how these changes have led, in turn, to yet additional insights (6) – in short I would like to take this opportunity to reappraise and update my original critique of the logical and historical structure of modern chemistry.

2. Five Basic Questions

My first discovery in the classroom was that the explicit use of energy and time as concept dimensions or categories, though logically viable, was a bit too a abstract for the novice and that I required a more user friendly approach. This resulted in my elaboration of the original three dimensions into what I call the five basic questions of chemistry. After first providing short lectures on the nature of both science and chemistry and arriving at a tentative definition of chemistry as "the study of substances, their characteristic properties and their mutual interconversions," I point out that, when presented with a new substance or material, a chemist will automatically ask five basic questions concerning it:

	Composition & Structure Dimension	Energy Dimension	Time Dimension
Molar Level	1. Relative composition by mass or volume of pure substances, solutions, and mixtures. Empirical designation of allomorphs (state, color, crystal form, α, β, etc.).	4. Calorimetric entropies & heats of formation. Free energies & equilibrium constants.	7. Experimental rate laws. Experimental Arrhenius parameters and/or heats & entropies of activation
Molecular Level	2. Absolute molecular compositional & structural formulas. Rationalization of allomorphs as either variations in composition (polymers) or structure (isomers).	5. Molecular interpretation of entropy. Interpretation of heats of formation in terms of atomization, average bond energies, etc. Molecular mechanics.	8. Molecular reaction mechanisms. Molecular interpretation of activation entropies and activated complexes.
Electrical Level	3. Electronic formulas (Lewis diagrams, electronic AO or MO configurations, etc.). Variations in either electronic or nuclear composition (ions & isotopes) or structure (excited states).	6. Calculation of energies based on electronic structure. Interpretation of spectra. Calculation of heats of atomization, spectroscopic entropies, etc.	9. Ionic and photochemical reaction mechanisms. Isotope effects. Calculation of activation energies. Various approximate reactivity indices.

Figure 2. The original classification of basic chemical concepts in terms of three dimensions and three levels of discourse.
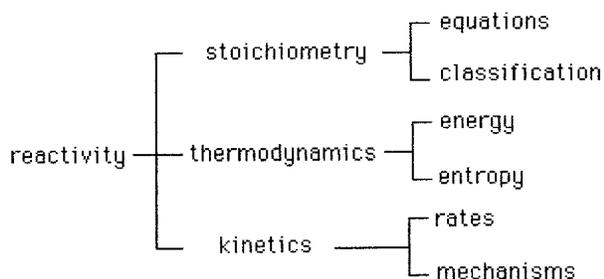
1. What is it made of?

2. How is it put together?

3. What can it change into?

4. How quickly will it change?

5. How complete is the change?

The answer to the first of these questions is technically known as the study of "composition," the answer to the second as the study of "structure," the answer to the third as the study of "stoichiometry," the answer to the fourth as the study of "kinetics," and the answer to the fifth as the study of "thermodynamics." Virtually all of the topics covered in a typical introductory chemistry course can be referred back to one of these five basic questions.

These questions may be further grouped into the two larger categories of "characterization," which entails the study of composition and structure:

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                        ┌─ composition
                        │
  characterization ─────┤
                        │
                        └─ structure
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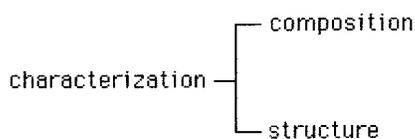
and "reactivity," which entails the study of stoichiometry, kinetics and thermodynamics:

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                     ┌─ stoichiometry ─┬─ equations
                     │                 └─ classification
                     │
  reactivity ────────┼─ thermodynamics ┬─ energy
                     │                  └─ entropy
                     │
                     └─ kinetics ───────┬─ rates
                                        └─ mechanisms
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Though the term stoichiometry is also traditionally used in connection with the study of composition and the calculation of empirical and molecular formulas for individual substances, I have restricted its use solely to the study of "reaction stoichiometry" as entailed in the writing of reaction statements for observed transformations, their proper classification (as additions, displacements, decompositions, etc.), and the usual mass, volume, and concentration calculations based on the resulting balanced equations.

3. The Physical Hierarchy

In a similar manner, I soon discovered that the three levels of molar, molecular and electrical also required further elaboration in order to accommodate the range of topics found in the typical textbook. In this case I introduced the concept of a physical or organizational hierarchy in which the entities at a given level of the hierarchy serve as the components of the entities on the level above it. Thus nucleons (protons and neutrons) are the components of atomic nuclei, nuclei and electrons are the components of atoms, atoms are the components of molecules, molecules are the components of phases, phases are the components of composite materials, and materials are the components of everyday macro objects (7).

Of course the levels just listed are only a small segment of the full physical hierarchy known to modern science. At the lower end nucleons are made of quarks and quarks, in turn, of still smaller parts, etc., whereas at the upper end individual macro objects make up economies, ecosystems and geospheres and these, in turn, make up planets, planets make up solar systems, solar systems make up galaxies etc. Those levels found among these higher and lower sections of the hierarchy are studied by sciences other than chemistry and, indeed, chemistry overlaps with several of them as one approaches the extremes of the hierarchy covered in a typical chemistry course – most notably with nuclear physics at the lower end and with materials science at the upper end.

The important point, however, is that the five basic questions may be asked of any of the five levels of the physical hierarchy covered in a typical chemistry course and, when this is done, it reveals some curious oversights as well as some novel ways of viewing conventional topics. Thus while the explicit application of the five questions to the molecular level is straight forward and unexceptional in the typical chemistry text, their application to the nuclear level is a good deal more ambiguous. Though we teach nuclear composition (counting protons and neutrons), most texts say nothing about nuclear structure, even though it plays a key role in determining nuclear stability. Likewise, though we teach nuclear stoichiometry (the writing and balancing of nuclear equations), decay constants and half lives, and calculate the energy release in typical nuclear reactions, we almost never explicitly point out that the second topic deals with the kinetics of nuclear reactions and the final topic with the thermodynamics of nuclear reactions.

This failure to maintain an explicit parallelism between the questions asked at the molecular level and those asked at the nuclear level means that many books

not only fail to explicitly point out significant similarities between the conceptual treatments of these two levels but significant differences as well. Thus while elements are conserved in chemical (i.e. molecular) reactions, only nucleons and charge are conserved in nuclear reactions. Likewise, while many chemical reactions are reversible and come to equilibrium before completion, nuclear reactions are irreversible and, if given sufficient time, will go to completion. And lastly, because of the enormous energy release involved in spontaneous nuclear reactions, the entropy effects so important in chemical reactions play only a minor role.

Likewise, composition at the nuclear and atomic levels is always expressed directly in terms of composition by number, which is to say by indicating the total numbers of each component particle present. At the molecular and phase levels, however, we not only use composition by number, but also composition by weight and composition by volume, with the latter two usages being far more common for phases than for molecules and becoming almost exclusive when we move further up the hierarchy to the level of material composition.

The relationship between the physical hierarchy and the molar, molecular and electrical levels used in the original lecture is somewhat complex since a given level of the physical hierarchy may often be described from several points of view. Thus we may describe phases at the molar level in terms of the phase rule and classical crystallography, or we may describe them at the molecular level in terms of the kinetic theory of matter. Likewise we may describe molecules at the molecular level using the kinetic theory of matter and classical chemical structure theory or at the electrical level using the electronic theory of bonding and structure.

4. The Barrier of Specialized Terminology

One problem which immediately occurs once one begins to ask the same questions at each level and to stress both parallelisms and differences, is the barrier which our conventional scientific terminology imposes on this integrative process. Here an understanding of the history of science once more has a significant role to play as this quickly reveals that much of this terminology is an historical accident in the sense that it was established at a time when these parallelisms were not recognized or it was originally introduced by specialists in other areas of science whose emphasis and objectives were quite different from those of the chemist.

Take, for example, the concept of isomerism used to describe species having different structures but identical compositions. This was introduced at the molecular level by chemists in the 1830s, but few students today realize that this important concept also occurs at the other levels of the hierarchy studied by chemists. Indeed, at the nuclear level this parallelism has long been explicitly acknowledged and, in recognition of this, nuclei corresponding to alternative structural arrangements of the same number of protons and neutrons are explicitly called nuclear isomers. However at the atomic level alternative arrangements of the identical number of electrons for a given atom are known as excited states rather than as atomic or electronic isomers, and at the phase level alternative arrangements of the component molecules in a solid crystal or liquid crystal are referred to as polymorphs rather than as phase isomers.

Likewise, at the phase level crystals having identical shapes but different compositions have, since the 1820s, been called isomorphs, but no such parallel term is generally accepted in chemistry to denote molecules having identical structures but differing compositions, whereas at the atomic level atoms and ions having different nuclei but identical electronic structures are said to be isoelectronic. Though I am confident that a similar variation must also exist at the nuclear level, I have never been able to locate a clear cut example, though I suspect that so-called mirror nuclei (inverted numbers of protons versus neutrons) may well qualify. How much simpler and enlightening – once these parallelisms are explicitly recognized – to use the terms: phase isomorph, molecular isomorph, electronic isomorph, and nuclear isomorph rather than the hodgepodge of traditional terms.

Unfortunately replacing traditional terms with newly coined terms of one's own making is heavily frowned upon in science – such revisions, when they occur, must come from above (i.e. from the high status research literature), but never from below (i.e. from the low status educational literature), and as a result introductory students are deprived of valuable insights and the opportunity to form a potentially more unified view of the subject matter of chemistry and physics. My own compromise in this matter is to always mention both the newer and the more traditional terms together.

5. The Fundamental Postulate of Chemistry

In addition to the table in figure 2, in Part I of the original lectures I further introduced what I referred to as the fundamental postulate of chemistry – namely the proposition that the specific molar or characteristic properties (Π) of substances are a function of their composition (c), structure (s), and temperature (T) – a result which may be generalized as:

$$\Pi = f(c, s, T, \varepsilon) \tag{1}$$

where ε subsumes any relevant environmental factors other than temperature, such as solvent effects, electrical potential for electrochemical systems, light intensity for photochemical systems, etc. and c and s may refer to composition and structure at any of the relevant levels of the physical hierarchy. The relevance of this postulate is that it not only justifies to students the reasons why both chemists and their own textbook have devoted so much time and effort to the study of composition and structure, but because it also speaks to the definition of chemistry given in the introductory lectures.

A ball tossed into the air will obey Newton's laws of motion irrespective of whether is colored blue, red, or white, irrespective of whether it is brittle or elastic, and irrespective of whether it is opaque or transparent or of whether it is an electrical conductor or an electrical insulator. These individual variations are irrelevant to the physicist who is studying the universal laws of matter. However, they are of cardinal interest to the chemist, who is largely interested in understanding the origins of different varieties of matter – otherwise known as substances – and thus of understanding why one substance is colored and another is not, why one substance is transparent and another opaque, why one substance is a good electrical conductor and another a poor conductor, why one substance smells like mint and another like rotten eggs, or of why one substance is toxic if ingested and another is nutritional, etc. To answer such questions is the primary purpose of the postulate in equation 1 and is the primary reason why chemists are obsessed with the study of composition and structure – namely the hope, that if they can fully implement this postulate, they will some day be able to both predict the properties of substances and to engineer them to predetermined specifications in the laboratory.

Unfortunately, while conventional chemistry texts devote a great deal of space to a discussion of the parameters on the right-hand side of equation 1, they say virtually nothing of the parameter on the left-hand side – which is to say virtually nothing concerning the definition and measurement of the characteristic properties used to identify and distinguish between different substances at the molar level – an oversight which required that I add a series of lectures to my course dealing with the definition and measurement of some simple representative electrical, mechanical, optical and physiological properties as a prelude to discussing how these properties correlated with what was known of the composition and structures of various substances at the material, phase, molecular and atomic levels.

In consulting various textbooks on materials science, optics, physiology, pharmacology and toxicology,
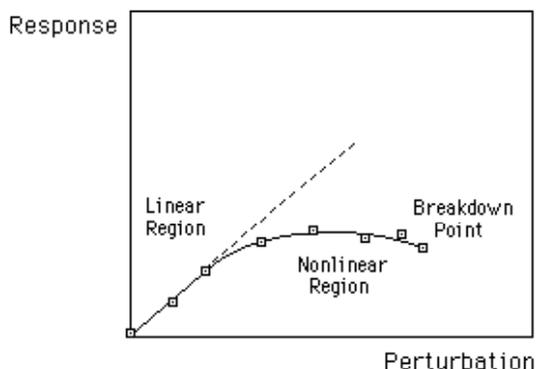

Figure 3. A generalized perturbation-response graph and its various characteristic regions. In general the nonlinear region may curve not only in the negative direction, as shown here, but also in a positive direction.

I soon discovered that the definition and measurement of simple properties in these diverse areas could all be fitted to a generalized perturbation-response graph (figure 3) in which various test samples (including, for some properties, living organisms) were subjected to various perturbations of increasing intensity – such as applied voltage, mechanical stress, increasing light intensity, increasing concentration or dosage, etc. – and the magnitude of their responses measured in terms of a second property – such as increasing current flow, increasing mechanical strain, increasing intensity of transmitted light, sound loudness, recovery rate or death rate, etc. The various characteristic regions of these graphs, and most particularly the slope of the initial linear response region, were then used to define the particular specific molar property of interest (e.g. specific electrical conductivity, optical transmittance, mechanical elasticity, physiological and drug sensitivity, etc.) which could then be correlated with variations in the composition and structure of the samples in question.

As with the case of terminology discussed in the previous section, this integrative process was once again inhibited by past conventions and arbitrary historical choices unique to certain areas of specialization. This was especially the case with mechanical properties which are normally plotted with the perturbation and response axes reversed and in which the resulting slope is interpreted in terms of material stiffness rather than material elasticity.

Despite the central importance of equation 1 to a full and comprehensive view of the nature of chemistry and its underlying assumptions, only advanced specialized chemical monographs ever address the issue of so-called structure-property correlations and they almost always do so only for the case of gases and liquids in which the effects of phase structure and material struc-

ture are eliminated through randomization, thus allowing a direct leap from the molar property to composition and structure at the molecular level. However, in the case of the solids studied by materials science this is no longer the situation and both phase structure and material structure can have a significant impact on the resulting molar properties as well – a complication which few chemists appreciate.

6. Where is the History of Chemistry?

So where in all of this is the history of chemistry? As already stated in the introduction, what I am really talking about in both my original lectures and in this update are the results of having used the history of chemistry to critically analyze the structure of modern chemistry and so arrive at a more unified and logically coherent presentation of its basic concepts rather than to argue that a modern course should include large doses of the history of chemistry *per se*. The reason for this is not that I object to the explicit use of history of chemistry as an integral part of the modern introductory course – I in fact demonstrated how this could be done in Part III of my original lecture series – but rather because such an explicit integration was impossible for myself given the current and future realities of the teaching of introductory college chemistry in the United States.

There was a time when this was not the case. In the 1960s there was a strong movement to integrate history of science with the teaching of introductory science courses designed for nonscience majors at both the high school and college levels and to emphasize both the cultural context of science and the nature of the scientific method. But by the time I began my teaching career in the 1980s this was no longer the case. American universities attracted fewer and fewer students interested in the humanities and the arts and more and more who were interested only in obtaining quick and highly employable degrees in such professional areas as the health sciences, engineering, business, and computer science. Though colleges continued to maintain the pretense that these students had to take a certain number general arts and science background courses before specializing, these requirements were largely a joke since the contents of these courses were, at least in the case of introductory chemistry, dictated by the demands of the schools of nursing and engineering rather than by the School of Arts and Sciences and the chemistry departments themselves.

As a result, introductory chemistry courses became "service" courses, rather than general science background courses. Their purpose was no longer to educate the typical college student by providing a balanced nonspecialized introductory overview of the nature and importance of the science in question but rather to provide specialized technical training for certain professions. As such, these courses were also used by the professional schools as proxies for entrance requirements. Since only students with grades of B or better in chemistry were allowed to continue in their professional programs and since, debarring flagrant grade inflation, only about 25% of the students by definition were going to fall into this category, the chemistry courses became populated with large numbers of frustrated and angry students who viewed the subject as so much of an impediment between them and their chosen careers. Any attempt to inject large doses of the history of chemistry into this unhappy situation would have been strenuously opposed by the professional schools who would have objected that their prospective students were neither being properly "trained" nor properly "screened."

If anything this situation has become much worse in recent years. Nearly a decade of financial stress and the increasing adoption of the corporate business model by American universities has resulted in a demand for interchangeable credit transfers and standardization of introductory courses through the use of a single standardized textbook and the taking of standardized exams. In large universities the content of the introductory chemistry courses is now dictated largely by the marketing departments of the book publishers and the instructors are being forced to increasingly teach to both the textbook and the exam. In addition, the recent demand that courses must be financially self-sustaining has resulted in larger and larger student to teacher ratios and the necessity of teaching chemistry courses in huge auditoriums which lack the proper facilities for chemical demonstrations and which are often not even located in the chemistry department.

Essentially these trends mean that chemistry departments are rapidly loosing control over their introductory courses. Even worse, they spell the death of any form of creative conceptual innovation – whether that be the introduction of historical subjects, new approaches to chemical concepts, or reorganization of the existing curriculum. These activities should be the life blood of a good university and their demise bodes ill for the future of American chemistry – not just because it eliminates critical thought but also because it will result in many creative individuals deciding against a future academic career in chemical education. What we have lost – I will not say, what we are in danger of loosing, since I think this is largely a *fait accompli* – has recently been elegantly summarized by Henry Bent (8):

A liberal education, it's said, is that which remains

after all that has been learned – about molecules and the chemical bond, perhaps – has been forgotten. Like Lewis Carroll's Cheshire Cat, what remains is the "grin" – skill, perhaps, in thinking creatively in inventing from evidence really "crazy" inductions, in any walk of life. Inductive sciences taught from historical points of view are "service courses" for citizens who live in societies based on invention and creativity

Given this reality, it is understandable why I have no wisdom to impart on how to directly introduce history of chemistry into the introductory chemistry curriculum. Indeed, it is something of a miracle that I was allowed as much academic freedom as I was to play with the conceptual content of my introductory chemistry course – a freedom which alas is now little more than a fond memory.

7. References and Notes

1. W. B. Jensen, "Logic, History, and the Chemistry Textbook: I. Does Chemistry Have a Logical Structure?," *J. Chem. Educ.*, **1998**, *75*, 679-687.

2. W. B. Jensen, "Logic, History, and the Chemistry Textbook: II. Can We Unmuddle the Chemistry Textbook?," *J. Chem. Educ.*, **1998**, *75*, 817-828.

3. W. B. Jensen, "Logic, History, and the Chemistry Textbook: III. One Chemical Revolution or Three?," *J. Chem. Educ.*, **1998**, *75*, 661-969.

4. W. B. Jensen, "Does Ontogeny Recapitulate Phylogeny in Chemical Education? Some Depressing Thoughts on Chemical Education and the History of Chemistry." Departmental Seminar, University of Cincinnati, 05 February, 1988.

5. A. Ladenburg, *Lectures on the History of the Development of Chemistry Since the Time of Lavoisier*, Alembic Club: Edinburgh, 1900, pp. 2-3

6. The topics in sections 2-5 are summaries of various sections of my lecture notes for my general chemistry course as found in W. B. Jensen, *Chemistry: The Science of Substance,* Department of Chemistry, University of Cincinnati, 2000. Copies available upon request.

7. There are, of course, ambiguities in this simplified account of the physical hierarchy. As pointed out in the original lectures, atoms as such do not truly persist within molecules, which at the electronic level are also made from nuclei and electrons. Thus while it is correct to say that molecules are made from atoms, it is not quite correct to say that they are made of atoms. Likewise several of the distinctions between the molecular and phase levels break down for the case of nonmolecular solids.

8. Correspondence with H. A. Bent, 08 March 2011.

Publication History