From Cathode Rays to Alpha Particles to Quantum of Action: A Rational Reconstruction of Structure of the Atom and Its Implications for Chemistry Textbooks

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ABSTRACT: Research in science education has recognized the importance of the history and philosophy of science. Given this perspective, it is important to analyze chemistry textbooks, at the freshman college level, to determine the degree to which they deal with recent developments in the history and philosophy of science. This study has the following objectives: (a) elaboration of a framework, based on a rational reconstruction of developments that led to the formulation of atomic models by Thomson, Rutherford, and Bohr; (b) formulation of eight criteria based on the framework that could be useful in the evaluation of chemistry textbooks; and (c) evaluation of the textbooks based on the criteria. Twenty-three textbooks were evaluated on the eight criteria. Results obtained show that most textbooks emphasize experimental details based on observations, leading to the presentation of scientific progress as a *rhetoric of conclusions,* based on irrevocable truths. Such an understanding lacks the conceptualization of the *heuristic principles* that led the scientists to design and interpret their experiments. For example, in the case of J. J. Thomson's work, besides the experimental details of cathode ray experiments (emphasized by most textbooks), the "heuristic principle" involved the testing of rival hypotheses, namely a determination of the mass-to-charge ratio would have helped to identify cathode ray particles as an ion or a universal charged particle. Most textbooks presented the experimental details, without the conceptualization that progress in science is based on competing frameworks of understanding that clash in the face of evidence. It is concluded that textbooks should emphasize not only the experimental details but also the "heuristic principles" required to "structure inquiry." © 1998 John Wiley & Sons, Inc. *Sci Ed* **82:**527–552, 1998.

INTRODUCTION

Recent research in science education has argued the importance of history and philosophy of science for science teaching (Burbules & Linn, 1991; Duschl, 1990; Hodson, 1988a; Kitchener,

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1993; Matthews, 1994; Niaz, 1994). Among other factors a major premise of this research is the parallel between the process of theory development by scientists and students' acquisition of knowledge (Carey, 1985, Chinn & Brewer, 1993; Duschl & Gitomer, 1991; Karmiloff-Smith & Inhelder, 1976; Kitchener, 1986, 1987; Piaget & Garcia, 1989). This interest has led to the investigation of how students' and teachers' beliefs about the nature of science can influence their understanding of science (Blanco & Niaz, 1997a; Gallagher, 1991; Hodson, 1993; Koulaides & Ogborn, 1989; Lederman, 1992; Lederman & O'Malley, 1990; Pomeroy, 1993; Ryan & Aikenhead, 1992; Solomon, Duveen, Scott, & McCarthy, 1992).

Siegel (1978) has emphasized the use of the history and philosophy of science if we want that science textbooks not be ". . . regarded as tools for inculcating in science students the principles and methods of the paradigm of the day. Rather, textbooks are to function as challengers to students" (p. 309). In contrast to Siegel, some educators, following Kuhn (1970), would like students to be immersed in current paradigms, eventually providing them the background for a critical appraisal (Hodson, 1988b; Lincoln, 1989). Stinner (1992), in a similar vein, has pointed out the ". . . need to clarify relationships between *experiment, hypothesis,* and *theory,* in scientific inquiry. The use of the model as a *heuristic* device would then allow an eclectic discussion of philosophical issues that would be independent of a school of thought. Moreover, repeated excursions into historical background will surely generate interest for the teacher and the student alike" (p. 14, italics in original). A recent study based on seven high school chemistry textbooks concluded: "All of the chemistry textbooks deemphasize science as a way of thinking. Their authors do not stress the importance of how chemists discover ideas and experiment, the historical development of chemistry concepts, cause-and-effect elationships, evidence and proof, and self-examination of one's thinking in the pursuit of knowledge" (Chiappetta, Sethna, & Fillman, 1991, p. 949).

According to Schwab (1974) scientific inquiry tends to look for patterns of change and relationships, which constitute the heuristic (explanatory) principles of our knowledge. In other words, "A fresh line of scientific research has its origins not in objective facts alone, but in a conception, a deliberate construction of the mind . . . this conception [heuristic principle] . . . tells us what facts to look for in the research. It tells us what meaning to assign these facts" (Schwab, 1974, p. 164). Monk and Osborne (1997) pointed out how many science curricula have forgotten Schwab's important epistemological distinction between the methodological (experimental data) and interpretative (heuristic principles) components. Matthews (1994) emphasized the importance of heuristic principles in scientific inquiry and science education in similar terms. To understand the function of "heuristic principles" let us consider J. J. Thomson's experimental work with cathode rays. Although the experimental details are important we cannot ignore the rationale behind Thomson's determination of the charge-to-mass ratio of cathode rays. This rationale, which helped Thomson to identify cathode rays as ions or universal charged particles (rival hypotheses), precisely constitutes the "heuristic principle." In a recent study, Blanco and Niaz (1997b) have shown how both students and teachers understand Thomson's experiments as a series of conclusions based on empirical findings (truths). In the case of Bohr's research program, Lakatos (1970) considers Bohr's explanation of the paradoxical stability of the Rutherford atom as the heuristic principle. In contrast, most textbooks consider Bohr's major contribution to be the explanation of the Balmer and Paschen series of the hydrogen line spectrum (i.e., experimental findings). This reminds us that almost 35 years ago we ignored Schwab's (1962) advice that science cannot be taught as an ". . . unmitigated *rhetoric of conclusions* in which the current and temporary constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24, emphasis in original).

Given this perspective it is important to analyze freshman college-level introductory chemistry textbooks to determine the degree to which they deal with recent developments in the history and philosophy of science.

The history of the structure of the atom since the late 19th and early 20th century shows that the models of J. J. Thomson, E. Rutherford, and N. Bohr evolved in quick succession and had to contend with competing models based on rival research programs. This period of the history of structure of the atom has been the subject of considerable debate and controversy in the history and philosophy of science literature (Achinstein, 1991; Falconer, 1987; Heilbron, 1985; Heilbron & Kuhn, 1969; Hettema, 1995; Holton, 1986, 1993; Jammer, 1966; Kuhn, 1984; Lakatos, 1970; Popper, 1965).

This study has the following objectives:

1. Elaboration of a framework, based on a rational reconstruction of developments that led to the formulation of atomic models by Thomson, Rutherford, and Bohr.
2. Formulation of criteria based on the framework that could be useful in the evaluation of chemistry textbooks.
3. Evaluation of freshman college-level chemistry textbooks utilizing the criteria based on the history and philosophy of science framework.

It is plausible to suggest that the evaluation of textbooks based on the criteria derived from a history and philosophy of science framework can provide teachers with insight as to how models or theories develop. Ignoring such developments by textbooks can deprive students of an opportunity to familiarize themselves with scientific practice and progress. Furthermore, according to Schwab (1974), it is important to understand not only the experimental details but also the heuristic principle that underlies the experimental findings:

> In physics, similarly, we did not know from the beginning that the properties of particles of matter are fundamental and determine the behavior of these particles, their relations to one another. It was not verified knowledge but a heuristic principle, needed to structure inquiry, that led us to investigate mass and charge and, later, spin. (Schwab, 1974, p. 165, emphasis added)

THOMSON'S CATHODE RAY EXPERIMENTS

This section will present details related to Thomson's experiments that are generally not presented in most textbooks. Furthermore, what most textbooks lack is the historical perspective and an interpretative framework to understand Thomson's experiments.

Cathode rays were first discovered by Plucker in 1858 (Falconer, 1987), long before Thomson became interested in them. Thomson's early views on the nature of electricity were within the accepted tradition of Maxwell's electrodynamics. The Maxwellian view of electricity was a strained state of the ether and discharge in the cathode rays tube was a relaxation of this strained state, with a consequent dissipation of energy. It is important to note that when Thomson conducted his experiments he was well aware of the controversy with regards to the nature of cathode rays: Were they particles or were they waves in the ether? (Achinstein, 1991, pp. 299–300; Falconer, 1987, p. 243). The controversy actually began in 1879 with Crookes' (1879) support for a particle theory of cathode rays. Deflection of cathode rays by a magnetic field was considered to provide strong support for a particle theory. Hertz (1883), on the other hand, showed that cathode rays were not deflected by an electrostatic field, contrary to the predictions of the particle theory (Falconer, 1987, p. 244). This finding provided support for the ether theory of cathode rays, according to which they were some sort of ethereal disturbance similar to light. Further support for the ether theory was provided by Goldstein (1880), Weidemann (1884), and Hertz (1892). Thomson's own thinking on the nature of cathode rays seems to have been ambivalent. As early as 1881, he (Thomson, 1881) seems to have conceived cathode rays as charged atoms, rather than charged molecules as Crookes had suggested earlier. Based on an unpublished draft of Thomson's book (*Notes on Recent Researches in Magnetism and Electricity*, Oxford, published in 1893), Falconer (1987, p. 247) concluded that Thomson was rather sympathetic to the ether theory of cathode rays. Surprisingly, however, as late as 1909 Thomson had this to say at a scientific meeting:

> The ether is not a fantastic creation of the speculative philosopher; it is as essential to us as the air we breathe . . . The study of this all-pervading substance is perhaps the most fascinating and important duty of the physicists. (Thomson, 1909)

This perhaps illustrates the importance of prior knowledge (alternative conceptions) both for scientists and students. Falconer (1987) further suggests that the controversy about the nature of cathode rays (German physicists generally supporting the ether theory, and the British supporting the particle theory) was not important to Thomson until 1895. It was the discovery of X-rays in 1895 that triggered Thomson and other physicists' interest in cathode rays. Interestingly, the number of publications referring to the nature of cathode rays increased abruptly from 4 in 1895 to 20 in 1896 (Falconer, 1987, p. 246).

Salient Aspects of Thomson's 1897 Article in the *Philosophical Magazine*

Given this new interest in the nature of cathode rays Thomson conducted a series of experiments at the beginning of 1897, which were first presented at a Friday evening discourse of the Royal Institution on April 29, 1897. An abstract was published in *The Electrician* (vol. 39, pp. 104–108) on May 21, 1897 and finally published at length in the *Philosophical Magazine* in October 1897 (Thomson, 1897). It is important to note the following important aspects of Thomson's now famous article:

1. In the very first sentence Thomson states the objective of the experiments; namely, to gain some information as to the nature of the cathode rays (p. 293).
2. In the second sentence he refers to the controversy with regard to the nature of cathode rays:

   > The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the aether . . . another view of these rays is that, so far from being wholly aetherial, they are wholly material . . . (p. 293)

   At this stage, Thomson seems to favor the particle theory (the article, of course, having been written after the experiments).
3. Thomson explains (deconstructs, according to Falconer [1987], p. 245) why Hertz (1883) could not obtain a deflection of the cathode rays electrostatically, and that it could only be obtained when the vacuum was a good one:

   > Hertz made the rays travel between two parallel plates of metal placed inside the discharge-tube, but found that they were not deflected when the plates were connected with a battery of storage-cells; on repeating this experiment I at first got the same result, but subsequent experiments showed that the absence of deflexion is due to the conductivity conferred on the rarefied gas by the cathode rays. On measuring this conductivity it was found that it diminished very rapidly as the exhaustion increased; it seemed then that on trying Hertz's experiment at very high exhaustions there might be a chance of detecting the deflexion of the cathode rays by an electrostatic force. (p. 296)

4. Thomson summarizes the properties of the cathode rays (found in most textbooks) and points out a fundamental aspect of his experiments; namely, the cathode rays are the same whatever the gas through which the discharge passes and concludes:

> As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. The question next arises, What are these particles? are they atoms, or molecules, or matter in a still finer state of subdivision? To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it. To determine this quantity, I have used two independent methods. (p. 302)

This perhaps is the most important aspect of Thomson's article, and shows clearly that he visualized that the determination of the mass (m) to charge (e) ratio (m/e) of the cathode rays would help him to identify the cathode ray particles as ions or a universal charged particle.

5. Thomson reports the results of the mass to charge (m/e) ratio of the cathode ray particles:

> . . . the value of m/e is independent of the nature of the gas, and its value 10^{-7} is very small compared with the value 10^{-4}, which is the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis. (p. 310)

Thomson goes on to speculate that the smallness of m/e may be due to the smallness of m or the largeness of e, or to a combination of both (p. 310). A little later in the article Thomson suggests that the smallness of m/e was due to both (p. 312).

6. In another important passage in the article, Thomson shares his thoughts with the reader:

> If, in the very intense electric field in the neighbourhood of the cathode, the molecules of the gas are dissociated and are split up, not into the ordinary chemical atoms, but into these primordial atoms, which we shall for brevity call corpuscles; and if these corpuscles are charged with electricity and projected from the cathode by the electric field, they would behave exactly like cathode rays. They would evidently give a value of m/e which is independent of the nature of the gas and its pressure, for the carriers are the same whatever the gas may be. (p. 311)

7. Thomson, of course, not only speculates and shares his thoughts with the reader but also suggests an explanation:

> The explanation which seems to me to account in the most simple and straightforward manner for the facts is founded on a view of the constitution of the chemical elements which has been favourably entertained by many chemists: *this view is that the atoms of the different chemical elements are different aggregations of atoms of the same kind.* In the form in which this hypothesis was enunciated by Prout, the atoms of the different elements were hydrogen atoms; in this precise form the hypothesis is not tenable, but if we substitute for hydrogen some unknown primordial substance X, there is nothing known which is inconsistent with this hypothesis, which is one that has been recently supported by Sir Norman Lockyer for reasons derived from the study of the stellar spectra. (p. 311, emphasis added)

Apparently, Thomson was pursuing various objectives at the same time. On the one hand, he disagreed with Prout's hypothesis, and on the other he wanted to formulate a new hypothesis (underlined part with atoms substituted by the primordial substance X). However, Thomson did not have any conclusive evidence for his new plausible hypothesis and hence he sought two allies, the chemists and Norman Lockyer. Lockyer (1881) had advanced a theory of a divisable atom to explain the different stellar spectra. Interestingly, Lockyer

(1897) had published his new theory in March 1897 just one month before Thomson proposed his corpuscle hypothesis. It is plausible to suggest that Thomson's hypothesis could be considered as the negative heuristic, hard core (Lakatos, 1970, p. 133), of his research program. According to Lakatos (1970) the hard core is irrefutable by the methodological decision of the protagonists—which, in Thomson's case, would perhaps be the chemists and Lockyer.

8. Thomson takes his hypothesis to yet another theoretical level by proposing two alternative models of the "chemical atom":

> Hypothesis: If we regard the chemical atom as an aggregation of a number of primordial atoms, the problem of finding the configurations of stable equilibrium for a number of equal particles acting on each other . . . , can be explained by two models:
>
> Model A: Law of force, for example, like that of Boscovitch, where the force between them is a repulsion when they are separated by less than a certain critical distance, and an attraction when they are separated by a greater distance.
>
> Model B: The simpler model of a number of mutually repellent particles held together by a central force. (p. 313)

9. As a grand finale, Thomson presents a theory of atomic structure:

> Thus on this view we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter—that is, matter derived from different sources such as hydrogen, oxygen, etc.—is of one and the same kind; this being the substance from which all the chemical elements are built up. (p. 312)

Thomson's Model of the Atom in Retrospect

Summarizing Thomson's 1897 article it can be observed that he goes far beyond a simple presentation of experimental results by speculating, hypothesizing, proposing models, offering explanations, and formulating a theory, which contrasts with the traditional view of the scientific method (cf. Niaz, 1994). Let us now look at how some of the other experimental physicists received Thomson's article at that time. Interestingly, FitzGerald (1897) proposed an alternative explanation for cathode rays based on "free electrons" in the same issue of *The Electrician* (May 21, 1897) in which an abstract of Thomson's article had appeared prior to publication in the *Philosophical Magazine* (October 1897). Apparently, FitzGerald accepted Thomson's hypothesis that cathode rays were corpuscles/primordial atoms/free electrons, but he questioned (precisely the "hard core") that these corpuscles were constituent parts of all atoms:

> This [FitzGerald's explanation] is somewhat like Prof. J. J. Thomson's hypothesis, except that it does not assume the electron to be a constituent part of an atom, nor that we are dissociating atoms, nor consequently that we are on the track of the alchemists. (FitzGerald, 1897, p. 104)

Determination of the mass-to-charge ratio (m/e) of the cathode rays can perhaps be considered the most important experimental contribution of Thomson's 1897 article. Yet, he was neither the first to do so nor the only experimental physicist. Schuster (1890) was perhaps the first to report (m/e) ratios for cathode rays, and his value came close to that of a charged nitrogen atom, which led him to conclude that cathode rays were charged atoms. Two German physicists, Kaufmann (1897) and Wiechert (1897), also determined (m/e) ratios of cathode rays in the same year as

Thomson and their measurements agreed with each other. Falconer (1987) explained cogently how Thomson's contribution differed from that of Kaufmann and Wiechert:

> Kaufmann, an ether theorist, was unable to make anything of his results. Wiechert, while realizing that cathode ray particles were extremely small and universal, lacked Thomson's tendency to speculation. He could not make the bold, unsubstantiated leap, to the idea that particles were constituents of atoms. Thus, while his work might have resolved the cathode ray controversy, he did not "discover the electron." (p. 251)

Apparently, Thomson's ability to speculate, elaborate alternative hypotheses and models, and perhaps most importantly formulate a theoretical framework for his experimental findings, led him to foresee and conceptualize what his contemporaries ignored. Thomson's interpretations have been the subject of criticism in the philosophy of science literature. Heilbron (1964), for example, claimed that Thomson's arguments were faulty as he claimed far more for the "corpuscle" than the data authorized and, furthermore, that few physicists in 1897 were prepared to believe, on this basis, that the world was made of corpuscles. Achinstein (1991), on the other hand, evaluated Thomson's theorization more favorably (p. 296). Thomson, although no philosopher of science, perhaps tried to respond to his critics in 1907 in the following terms:

> From the point of view of the physicist, a theory of matter is a policy rather than a creed; its object is to connect or coordinate apparently diverse phenomena, and above all to suggest, stimulate and direct experiment. It ought to furnish a compass which, if followed, will lead the observer further and further into previously unexplored regions. (Thomson, 1907, p. 1)

RUTHERFORD'S ALPHA PARTICLE EXPERIMENTS

Before turning his attention to the structure of the atom, Rutherford's (1904, 1906, 1913) main research interest was radioactivity. In their efforts to characterize the nature of the alpha particle, Rutherford and colleagues (Geiger and Marsden) had observed something entirely unexpected and troublesome—"scattering" of alpha particles—the deflection of alpha particles from their true line of flight as they passed through matter. In a letter to Baumbach (Rutherford's glass-blower), written in the summer of 1908, Rutherford complained: "The scattering is the devil" (reproduced in Wilson, 1983, p. 286). However:

> In 1908 the scattering was a technical problem to be overcome—but, as with so many other of Rutherford's great leaps of scientific imagination, when the experiment was over he asked Geiger to look into scattering as a phenomenon in its own right. And from this fascination with the small anomaly great results were to be achieved. (Wilson, 1983, p. 287)

Later in life Rutherford was fond of recounting how Geiger had suggested that the young Marsden could perhaps start working on a small research project. Rutherford's response to Geiger was indeed prophetic: "Why not let him see if any alpha particles can be scattered through a large angle?" (reproduced in Wilson, 1983, p. 291). It did not take long for Geiger and Marsden (1909) to report that beta particles bouncing back off a metal plate was a well-known phenomenon, but their findings were extraordinary: "A small fraction of alpha particles falling upon a metal have their directions changed to such an extent that they emerge again at the side of incidence" (p. 495). Further experiments confirmed the well-known phenomenon of the deflection of alpha particles, described in most textbooks. The birth of the nuclear atom itself can perhaps be traced to a dinner conversation at Rutherford's residence, just before Christmas, 1910, as "after supper the nuclear theory came out" (Darwin, 1962).

Rutherford announced his hypothesis of the nuclear atom for the first time on March 7, 1911 at a meeting of the Manchester Literary and Philosophical Society, which was later submitted in April and published in the *Philosophical Magazine,* May 1911 (Rutherford, 1911).

Salient Aspects of Rutherford's 1911 Article in the *Philosophical Magazine*

1. In the very first paragraph, Rutherford starts on a controversial note by pointing out that:

   > It has generally been supposed that the scattering of a pencil of alpha or beta rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. (p. 669)

   This of course referred to the experimental work of Crowther (Proceedings of the Royal Society, 1xxxiv, 1910, p. 226), a colleague of Thomson. Based on Crowther's work, Thomson propounded the *compound scattering hypothesis,* as a rival to the *single scattering hypothesis,* of Rutherford. Rutherford goes on to explain briefly that Thomson's model of the atom is supposed to:

   > . . . consist of a number N of negatively charged corpuscles, accompanied by an equal quantity of positive electricity uniformly distributed throughout a sphere. (p. 670)

   Rutherford explicitly points out that Crowther's experimental results provided support for Thomson's hypothesis of compound scattering:

   > The theory of Sir J. J. Thomson is based on the assumption that the scattering due to a single atomic encounter is small, and the particular structure assumed for the atom does not admit of a very large deflexion of an alpha particle in traversing a single atom, unless it be supposed that the diameter of the sphere of positive electricity is minute compared with the diameter of the influence of the atom. (p. 670)

   In the last part of the sentence Rutherford was preparing the ground for his own model of the atom.
2. Rutherford now presents the other side of the story:

   > The observations, however, of Geiger and Marsden [1909] on the scattering of alpha rays indicate that some of the alpha particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident alpha particles, about 1 in 20,000 were turned through an average angle of 90° in passing through a layer of gold-foil about .00004 cm. thick, . . . A simple calculation based on the theory of probability shows that the chance of an alpha particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the alpha particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that *the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.* (p. 669, emphasis added)

   This summarized, on the very first page of the article, the experimental work of Rutherford's colleagues, his hypothesis of single scattering, and a glimpse of his nuclear atom.

3. Later in the article Rutherford provides calculations and emphasizes that the probability of a second deflection is negligible:

   > . . . it is assumed that the alpha particles scattered through a large angle suffer only one large deflexion. If, for example, the probability of a single deflexion ϕ in passing through a thickness t is 1/1000, the probability of two successive deflexions each of value ϕ is $1/10^6$, and is negligibly small. (p. 675)

4. Besides Thomson's model of the atom, Rutherford also mentions another rival, Nagaoka's (1904) "Saturnian" model of the atom, which consisted of a central attracting mass surrounded by rings of electrons. Nagaoka showed that such a system was stable if the attractive force was large. With regard to Nagaoka's model, Rutherford explained: ". . . the chance of large deflexion would practically be unaltered, whether the atom is considered to be a disk or a sphere" (p. 688).
5. It is of interest to note that until April 1911, when this article was written, Rutherford makes no mention of:
   (a) An analogy of his model to the solar system.
   (b) Nucleus, to represent the central charge of the atom.
   (c) Whether the central charge was positive or negative.

   With respect to the central charge, Rutherford explicitly stated that, ". . . it has not so far been found possible to obtain definite evidence to determine whether it be positive or negative" (p. 688). This shows the tentative nature of Rutherford's model of the atom.

Rutherford's Model of the Nuclear Atom in Retrospect

In this section we consider information available in the literature that could facilitate a reconstruction of the events leading to the postulation of Rutherford's model. Apparently, Rutherford had the experimental data as early as June 1909 (Geiger & Marsden, 1909) to postulate his model of the nuclear atom. It is of interest to reconstruct the events that finally led Rutherford to announce his model on March 7, 1911 at a meeting of Manchester Literary and Philosophical Society, and ultimately to publish them in the *Philosophical Magazine* in May of 1911. What happened between June 1909 and March 1911? In his presidential address to the annual meeting of the British Association, Winnipeg, Canada, held in the summer of 1909, Rutherford was referring to the recent article of Geiger and Marsden (1909), when he reported:

> The conclusion is unavoidable that the atom is the seat of an intense electric field, for otherwise it would be impossible to change the direction of the particle in passing over such a minute distance as the diameter of a molecule. (reproduced in Wilson, 1983, p. 292)

Crowther (1910) published experimental findings that provided evidence for Thomson's (1910) hypothesis of compound scattering of alpha particles. This apparently forced Rutherford, Geiger, and Marsden to do further experiments before facing the challenge of Thomson and colleagues. According to Wilson (1983):

> J. J. [Thomson] had people working on the scattering problem in his own laboratory, and a paper by one of his men, Crowther [1910], became of crucial importance in the battle between the two concepts of the atom. It is, however, too often ignored that Rutherford's superior concept of atomic structure also involved the overthrow of his master's [Thomson] model . . . (p. 295)

In a series of letters written to friends and colleagues, just before announcing his hypothesis of the nuclear atom on March 7, 1911, Rutherford acknowledges the serious challenge posed by the rival hypothesis; namely, Thomson's hypothesis of compound scattering, based on Crowther's experimental work. Following are excerpts of Rutherford's letters:

> Dec. 14, 1910: I think I can devise an atom much superior to J. J.'s [Thomson] for the explanation of and stoppage of alpha- and beta-particles, and at the same time I think it will fit in extraordinarily well with the experimental numbers. It will account for the reflected alpha-particles observed by Geiger and generally I think will make *a fine working hypothesis.* (letter to Boltwood, reproduced in Wilson [1983], p. 295, emphasis added)
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> Feb. 8, 1911: [Geiger's results] look very promising for the theory. I am beginning to think that the central core is negatively charged, for otherwise the law of absorption for beta-rays would be very different from that observed . . . (letter to Bragg, reproduced in Wilson [1983], p. 300)
>
> Feb. 9, 1911: I have looked into Crowther's scattering paper carefully, and the more I examine it the more I marvel at the way he made it fit (or thought he made it fit) J. J.'s theory . . . Altogether I think the outlook is decidedly promising. (letter to Bragg, reproduced in Wilson [1983], p. 300)
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> Feb. 11, 1911: I am quite sure the numbers of the earlier part of the curve [Crowther's] were fudged. (letter to Bragg, reproduced in Wilson [1983], pp. 300–301)
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> March 8, 1911: I may mention that the theory of large [single] scattering will hold equally well if instead of one large central charge one supposed the atom to consist of a very large number of smaller charges distributed throughout the atom. It can be shown however that, on this view, the small scattering should be much greater than that experimentally observed. It is consequently simplest to consider the effect of a single point charge. (letter to Madsen, reproduced in Wilson [1983], p. 302)

The last letter, written the day after his address to the Manchester Literary and Philosophical Society on March 7, 1911, is indeed a strange demonstration of ambivalence. In a sense it shows the power and acceptance of the rival theory (Thomson's compound scattering) in the scientific community. On the one hand, Rutherford was entirely convinced and optimistic that his model of the atom explained experimental findings better, and yet it seems that the prestige, authority, and even perhaps some reverence for his teacher made him waver. However, in a letter to Schuster (Secretary of the Royal Society), written about 3 years later (Feb. 2, 1914), Rutherford is much more forceful:

> . . . I have promulgated views on which J. J. [Thomson] is, or pretends to be, sceptical. At the same time I think that if he had not put forward a theoretical atom himself, he would have come round long ago, for the evidence is very strongly against him. If he has a proper scientific spirit I do not see why he should hold aloof and the mere fact that he was in opposition would liven up the meeting. (reproduced in Wilson [1983], p. 338)

Crowther (1974) himself, recounting the events many years later, set the record straight:

> J. J. [Thomson] used Crowther's results in elaborating his theory of the atom as a region of positive electrification, in which electrons were distributed like plums in a pudding. Rutherford closely analysed Crowther's experiments, and concluded that they did not provide valid evidence for this model. (p. 151)

In retrospect, another aspect of Rutherford's experiments that deserves more attention is that only a very small fraction (1 in 20,000) of the alpha particles deflected through large angles. Furthermore, based on the theory of probability, Rutherford showed that: (a) the chance of an alpha particle being deflected through large angles was "vanishingly small"; and (b) the probability of an alpha particle experiencing a second deflection was “negligibly small.” It was precisely for these reasons that he and others found the hypothesis of single scattering, and a model of the atom with an “intense electric field,” so convincing. Interestingly, early in 1909, Rutherford enrolled to attend elementary lectures on probability given by Horace Lamb, and his notebooks bear witness to his attendance and having taken extensive notes (Wilson, 1983, p. 290). Herron (1977), for example, has emphasized that students get the impression that the surprising part of these experiments was that most alpha particles passed through the gold foil undeflected, whereas:

> . . . It was the 1 in 20,000 particles deflected through large angles that led Rutherford to postulate that the positive charge in the atom is concentrated in a small region of space at its center and the idea of a nuclear atom became established as the accepted theory. (p. 499)

Looking back on Rutherford’s work many years later, Millikan (1947) emphasized a similar point

> These sharp deflections, which occasionally amount to as much as 150° to 180°, lend the strongest of support to the view that the atom consists of a heavy positively charged nucleus about which are grouped enough electrons to render the whole atom neutral. But the fact that in these experiments the *alpha particle goes through 130,000 atoms without approaching near enough to this central nucleus to suffer appreciable deflection more than two or three times constitutes the most convincing evidence . . . [of] . . . this central nucleus . . .* (p. 193, emphasis added)

Finally, according to Wilson (1983):

> Rutherford’s nuclear atom did not prevail because of direct evidence in its favour—it prevailed because of its extraordinarily successful explanatory power . . . explanations for large areas of problems in chemistry, particularly regarding the nature of the elements and the regularities and differences between them. (p. 306)

BOHR’S MODEL OF THE ATOM

Little did Bohr know what was awaiting him when he arrived in Cambridge in September of 1911 to work with J. J. Thomson, then considered to be a “. . . pioneer of the electron theory of metals and the acknowledged world master in the design of atomic models” (Heilbron & Kuhn, 1969, p. 223). Earlier in the year, in May 1911, he had successfully defended in Copenhagen his doctoral dissertation based on the electron theory of metals. Bohr had brought a rough English translation of his dissertation, which he wanted Thomson to read. After months of waiting, with the dissertation among the pile of manuscripts on Thomson’s desk, Bohr decided to go and work with Rutherford in Manchester. Thus, “. . . Thomson had the unfortunate distinction of losing for the Cavendish [Laboratory] both Rutherford and Bohr, founders of modern physics” (Snow, 1981, p. 52). Bohr arrived in Manchester in March 1912 and, after some experimental work on radioactivity, started working to quantize Rutherford’s atom. In July 1912 Bohr submitted a preliminary draft to Rutherford, which he himself labeled as: “First draft of the considerations contained in the paper ‘On the constitution of atoms and molecules’ (written up to show these considerations to Prof. Rutherford)/(June and July 1912).” Heilbron and Kuhn (1969) consider this first draft to be a crucial document in the history of quantum theory, and refer to it as the “Rutherford Memorandum” (p. 244). Bohr’s style of work was indeed unique if not enigmatic, which has led some philosophers of science to ask:

> What suddenly turned his attention from electron theory to atom models during June 1912? Why did he then choose to develop the new, little-known Rutherford atom rather than, say, the older, more successful model proposed by J. J. Thomson? Why did he approach the quantization problem

> in the particular way he did, one which bore impressive fruits at once and which, a year later, began to revolutionize physics? (Heilbron & Kuhn, 1969, p. 212)

Nevertheless, it took several months before Bohr submitted the final draft to Rutherford on March 6, 1913. It was accepted by the *Philosophical Magazine* on April 5 and published in July 1913 as the first part of a trilogy (Bohr, 1913).

Salient Aspects of Bohr's 1913 Article in the *Philosophical Magazine*

1. Bohr starts the first part of his trilogy with the following words: "In order to explain the results of experiments on scattering of alpha rays by matter Prof. Rutherford has given a theory of the structure of atoms" (p. 1). Next, Bohr briefly describes Rutherford's model of the atom.
2. In the next paragraph Bohr points out difficulties with Rutherford's model of the atom:

   > In an attempt to explain some of the properties of matter on the basis of this atom-model we meet, however, with difficulties of a serious nature arising from the apparent instability of the system of electrons: difficulties purposely avoided in atom-models previously considered, for instance, in the one proposed by Sir J. J. Thomson. According to the theory of the latter the atom consists of a sphere of uniform positive electrification, inside which the electrons move in circular orbits. (p. 2)

3. In the third paragraph Bohr makes a comparison of the Thomson and Rutherford models:

   > The principal difference . . . consists in the circumstance that the forces acting on the electrons in the atom-model of Thomson allow of certain configurations and motions of the electrons for which the system is in a stable equilibrium; such configurations, however, apparently do not exist for the second atom-model. (p. 2)

   It is important to observe that, although the Thomson model could not be sustained after Rutherford's alpha particle experiments, it did provide for stability.
4. In the fourth paragraph Bohr formulates his epoch-making postulate:

   > The way of considering a problem of this kind has, however, undergone essential alterations in recent years owing to . . . experiments on very different phenomena such as specific heats, photoelectric effect, Röntgen-rays, etc. The result of the discussion of these questions seems to be a general acknowledgement of the inadequacy of the classical electrodynamics in describing the behaviour of systems of atomic size . . . it seems necessary to introduce in the laws in question a quantity foreign to the classical electrodynamics, i.e., Planck's constant, or as it often is called the elementary *quantum of action.* (p. 2, emphasis added)

5. Next, Bohr points out that based on his model, it is possible to take into account the law of the line spectrum of hydrogen, leading to the Balmer, Paschen, and the other series. Although the details of Bohr's calculations for energy emission during electron transition are well known, this aspect of his theory has been the subject of considerable research and controversy in the philosophy of science literature, and will be discussed in the next section.
6. Bohr constantly refers to a rival theory by J. W. Nicholson (1911, 1912), which also presented a quantized version of the atomic model:

   > Nicholson has obtained a relation to Planck's theory showing that the ratios between the wavelength of different sets of lines of the coronal spectrum can be accounted for with great accuracy

> by assuming that the ratio between the energy of the system and the frequency of rotation of the ring is equal to an entire multiple of Planck's constant. (p. 6)

Bohr then presents a considerably detailed critique of Nicholson's model. The important point is that Bohr had to contend with a rival model. Details of this challenge to Bohr's model will be discussed in the next section.

Bohr's Model of the Atom in Retrospect

Interpretation of Bohr's model of the atom by philosophers of science is very instructive for science teachers. Bohr's main objective was to explain the paradoxical stability of the Rutherford atom, and still most textbooks consider Bohr's major contribution to be the explanation of the Balmer and Paschen series of the hydrogen line spectrum. According to Lakatos (1970):

> . . . Bohr's problem was not to explain Balmer's and Paschen's series, but to explain the paradoxical stability of the Rutherford atom. Moreover, Bohr had not even heard of these formulae before he wrote the first version of his paper. (p. 147)

The "first version" Lakatos is referring to is of course the "Rutherford Memorandum" written in June–July of 1912 (cf. Heilbron & Kuhn, 1969, p. 244). A letter, written by Bohr to Rutherford on Jan. 31, 1913, shows that even then he was not fully aware of the implications of spectroscopic research for his problem:

> I do not at all deal with the question of calculation of the frequencies corresponding to the lines in the visible spectrum. I have only tried, on the basis of the simple hypothesis, which I used from the beginning, to discuss the constitution of the atoms and molecules in their "permanent state." (reproduced in Rosenfeld [1963], pp. xxxvi–xxxvii)

Actually, Bohr was quite skeptical about the relevance of spectra for his model of the atom. Many years later, in an interview with Thomas Kuhn in 1962, Bohr expressed this quite explicitly:

> The spectra was a very difficult problem . . . Just as if you have the wing of a butterfly, then certainly it is very regular with the colors and so on, but nobody thought that one could get the basis of biology from the coloring of the wing of a butterfly. (reproduced in Heilbron & Kuhn, 1969, p. 257)

Apparently, it was the spectroscopist, H. M. Hansen who familiarized Bohr with the spectroscopic work and its implications for his model (cf. Jammer, 1966, p. 77). Having seen the importance of the spectra Bohr is said to have repeated often: "As soon as I saw Balmer's formula, the whole thing was immediately clear to me" (reproduced in Rosenfeld [1963], p. xxxix). Interestingly, Kuhn points out that even before the "Rutherford Memorandum" was discovered in Bohr's files, he had conjectured:

> . . . that Bohr had developed a detailed, non-spectroscopic, quantized version of Rutherford's atom some time before he saw the relevance of the Balmer formula. (Heilbron & Kuhn, 1969, p. 255)

A reconstruction of these events related to the development of the structure of the atom provides an understanding as to how science progresses and is practiced. Lakatos (1970) has shown the importance of these events in the history of science in the following terms:

> Since the Balmer and the Paschen series were known before 1913 [year of Bohr's first publication], some historians present the story as an example of a Baconian "inductive ascent": (1) the chaos of spectrum lines, (2) an "empirical law" (Balmer), (3) the theoretical explanation (Bohr). (p. 147)

Lakatos clearly uses this episode in the history of science to emphasize that science does not proceed from experimental observations to scientific laws and theories, through inductive generalizations. In spite of their many differences, most new philosophers of science would agree to this conceptualization of scientific progress (cf. Feyerabend, 1970; Hanson, 1958; Kuhn, 1970, Lakatos, 1970; Laudan, 1977). This perspective based on the new philosophy of science can be summarized as:

> The role of observation is not to provide a firm basis from which generalizations can then be inductively extrapolated but, if anything, to provide some check on whether the promise of previously made theoretical commitments has been fulfilled. (Papineau, 1979, p. 100)

Once again, Lakatos (1970) expresses the argument cogently:

> . . . the progress of science would hardly have been delayed had we lacked the laudible trials and errors of the ingenious Swiss school-teacher [Balmer]: the speculative mainline of science, carried forward by bold speculations of Planck, Rutherford, Einstein and Bohr would have produced Balmer's results deductively, as test-statements of their theories, without Balmer's so-called "pioneering." In the rational reconstruction of science there is little reward for the pains of the discoverers of "naive conjectures." (p. 147)

An important aspect of Bohr's model of the atom is the presence of a deep philosophical chasm: that is, in the stationary states, the atom obeys classical laws of Newtonian mechanics; on the other hand, when the atom emits radiation, it exhibits discontinuous (quantum) behavior, according to laws first proposed by Planck in 1900. Rutherford, although no philosopher of science, was the first to point this out, when he wrote to Bohr on March 20, 1913:

> . . . the mixture of Planck's ideas with the old mechanics makes it very difficult to form a physical idea of what is the basis of it all . . . How does the electron decide what frequency it is going to vibrate at when it passes from one stationary state to another? (reproduced in Holton [1993], p. 80)

Bohr's 1913 article, in general, had a fairly adverse reception in the scientific community. Otto Stern told a friend: "If that nonsense is correct which Bohr has just published, then I will give up being a physicist" (reproduced in Holton [1986], p. 145). Lord Rayleigh was categorical: "It does not suit me" (reproduced in Holton [1993], p. 79). H. A. Lorentz objected: ". . . the individual existence of quanta in the aether is impossible . . ." (reproduced in Holton [1993], p. 79). J. J. Thomson, whom Bohr considered as the "world master in the design of atomic models" objected to Bohr's conception in most of his writings from 1913 to 1936 (cf. Holton, 1993, p. 79).

More recently, philosophers of science have been more understanding of Bohr's model of the atom:

> . . . it is understandable that, in the excitement over its success, men overlooked a malformation in the theory's architecture; for Bohr's atom sat like a baroque tower upon the Gothic base of classical electrodynamics. (Margenau, 1950, p. 311)

> Thus Bohr's atom of 1913 was really a kind of mermaid—the improbable grafting together of disparate parts, rather than a new creation incorporating quantum theory at its core. (Holton, 1986, p. 145)

These appreciations (Margenau and Holton), written many years after Bohr's publication in 1913, still lack a historical perspective, as to what exactly Bohr was doing. Lakatos, on the other hand, shows that Bohr used a methodology used frequently by scientists in the past and perfectly valid for the advancement of science:

> . . . *some of the most important research programmes in the history of science were grafted on to older programmes with which they were blatantly inconsistent.* For instance, Copernican astronomy was "grafted" on to Aristotelian physics, Bohr's programme on to Maxwell's. Such "grafts" are irrational for the justificationist and for the naive falsificationist, neither of whom can countenance growth on inconsistent foundations . . . As the young grafted programme strengthens, the peaceful co-existence comes to an end, the symbiosis becomes competitive and the champions of the new programme try to replace the old programme altogether. (Lakatos, 1970, p. 142, italics in original)

CRITERIA FOR THE EVALUATION OF CHEMISTRY TEXTBOOKS

Based on the historical perspective (rational reconstruction) presented in the previous sections here we present criteria for the evaluation of freshman college-level introductory chemistry textbooks. The following classifications were generated to evaluate the textbooks:

- Satisfactory (S): Treatment of the subject in the textbook is considered to be satisfactory if the role of conflicting frameworks based on competing models of the atom is briefly described.
- Mention (M): A simple mention of the conflicting frameworks or controversy with no details.
- No mention (N): No mention of the conflicting frameworks.

To refer to the criteria based on the three models, the following symbols are used: T = Thomson; R = Rutherford; and B = Bohr.

T1—*Cathode rays as charged particles or waves in the ether.* Thomson's experiments were conducted against the backdrop of a conflicting framework. Thomson (1897) explicitly points out that his experiments were conducted to clarify the controversy with regard to the nature of the cathode rays; that is, charged particles or waves in the ether. This criterion is based on: Thomson (1897), salient aspects 2 and 3; Achinstein (1991); and Falconer (1987).

T2—*Determination of mass-to-charge ratio to decide whether cathode rays were ions or a universal charged particle.* Thomson decided to measure mass-to-charge ratio to identify cathode rays as ions (if the ratio was not constant) or as a universal charged particle (constant ratio for all gases). This criterion is based on: Thomson (1897), salient aspects 4, 5, and 6; Achinstein (1991); Heilbron (1964); and Niaz (1994).

R1—*Nuclear atom.* Rutherford's experiments with alpha particles and the resulting model of the nuclear atom had to compete with a rival framework, namely Thomson's model of the atom (referred to as "plum-pudding" in most textbooks). This criterion is based on: Rutherford (1911), salient aspect 1; and Niaz (1994).

R2—*Probability of large deflections is exceedingly small as the atom is the seat of an intense electric field.* The crucial argument that clinched the argument in favor of Rutherford's model was not the large angle deflection of alpha particles (an important finding), but rather the knowledge that 1 in 20,000 particles deflected through large angles. This criterion is based on: Rutherford (1911), salient aspects 2 and 3); Herron (1977); and Millikan (1947).

R3—*Single/compound scattering of alpha particles.* To maintain his model of the atom and to explain large angle deflections of alpha particles, Thomson put forward the hypothesis of compound scattering (multitudes of small scatterings). The rivalry between Rutherford's hypothesis of single scattering based on a single encounter and Thomson's hypothesis of compound scattering led to a bitter dispute between the proponents of the two hypotheses. This criterion is based on: Rutherford (1911), salient aspect 1; Crowther (1910); and Wilson (1983).

B1—*Paradoxical stability of the Rutherford model of the atom.* Bohr's main objective was to explain the paradoxical stability of the Rutherford model of the atom, which constituted a rival framework for his own model. This criterion is based on: Bohr (1913), salient aspects 1, 2, and 3; Lakatos (1970); and Niaz (1994).

B2—*Explanation of the hydrogen line spectrum.* Bohr had not even heard of the Balmer and Paschen formulas for the hydrogen line spectrum, when he wrote the first version of his 1913 article. Failure to understand this episode within a historical perspective led to an inductivist/positivist interpretation, referred to as the "Baconian inductive ascent" by Lakatos (1970). Interestingly, Kuhn and Lakatos, in spite of their so many differences, agree that Bohr's major contribution was the quantization of the Rutherford model of the atom. This criterion is based on: Bohr (1913), salient aspect 5; Heilbron and Kuhn (1969); Lakatos (1970); and Niaz (1994).

B3—*Deep philosophical chasm.* Bohr's incorporation of Planck's "quantum of action" to the classical electrodynamics of Maxwell, represented a strange "mixture" for many of Bohr's contemporaries and philosophers of science. This episode illustrates how scientists, when faced with difficulties, often resort to such contradictory "grafts." This criterion is based on: Bohr (1913), salient aspect 4; Holton (1986); Margenau (1950); and Lakatos (1970).

The rational reconstruction presented in the previous sections facilitates the understanding that these criteria (T1, T2, R1, R2, R3, B1, B2, and B3) represent the "heuristic principles" (Schwab, 1974) that underlie the work of Thomson, Rutherford, and Bohr.

To implement the criteria, a university chemistry professor with a Ph.D. in chemistry and 20 years of teaching experience at both the freshman and higher levels, and the present author, applied the criteria separately to evaluate three textbooks (selected randomly). It was found that both evaluators coincided on the evaluation of six criteria on one textbook, seven criteria on another, and all eight criteria on the third textbook. Each evaluator explained the points of disagreement and, after some discussion, consensus was achieved. With this experience, the rest of the textbooks were then evaluated by the author. It is important to note that the other evaluator was provided the first four sections of this manuscript, before evaluation, to gain familiarity with the historical antecedents of the work of Thomson, Rutherford, and Bohr.

Evaluation of Chemistry Textbooks Based on Space Utilized, Mathematical Details, Illustrations of Experimental Apparatus, and Models

Besides the criteria just mentioned, textbooks were also evaluated on the following additional criteria, considered to be related to those based on a history and philosophy of science framework:

1. Space (S) utilized by the textbooks; that is, number of pages used for presenting the work of Thomson, Rutherford, and Bohr.
2. Mathematical (M) details that complement/help to understand the atomic model.
3. Illustrations (IA) of experimental apparatus used by Thomson and Rutherford.
4. Illustrations (IM) of the atomic models of Thomson, Rutherford, and Bohr.

EVALUATION OF CHEMISTRY TEXTBOOKS: RESULTS AND DISCUSSION

Thomson (Criteria T1 and T2)

Table 1 shows that only two textbooks mentioned (M) that Thomson's experiments were conducted against the backdrop of a conflicting framework; namely cathode rays could have been

TABLE 1
Evaluation of Chemistry Textbooks Based on a History and Philosophy of Science Framework[a]

		Criteria							
No.	Textbook	T1	T2	R1	R2	R3	B1	B2	B3
1	Ander & Sonessa (1981)	N	N	N	N	N	M	N	N
2	Anderson et al. (1973)	N	N	N	N	N	N	N	N
3	Bodner & Pardue (1989)	M	N	N	S	N	N	N	S
4	Brady & Holum (1981)	N	N	N	N	N	N	N	N
5	Brown & LeMay (1988)	N	N	M	N	N	N	N	N
6	Chang (1981)	N	N	S	N	N	N	N	N
7	Dickerson et al. (1984)	N	N	M	N	N	S	N	S
8	Hein (1990)	N	N	N	N	N	N	N	N
9	Holtzclaw & Robinson (1988)	N	N	N	N	N	M	N	N
10	Joesten et al. (1991)	N	N	N	N	N	N	N	M
11	Mahan & Myers (1990)	N	S	M	N	N	S	N	N
12	Masterson et al. (1985)	N	N	N	N	N	N	N	N
13	Mortimer (1983)	N	N	N	N	N	N	N	N
14	Newell (1977)	N	N	M	N	N	N	N	N
15	Oxtoby et al. (1990)	M	N	S	N	N	M	N	N
16	Quagliano & Vallarino (1969)	N	N	N	N	N	N	N	N
17	Segal (1989)	N	S	S	N	N	S	N	M
18	Sienko & Plane (1971)	N	N	S	N	N	M	N	M
19	Sisler et al. (1980)	N	N	N	S	N	N	N	M
20	Stoker (1990)	N	N	S	N	N	N	N	N
21	Whitten et al. (1992)	N	N	N	N	N	N	N	N
22	Wolfe (1988)	N	N	S	N	N	N	N	N
23	Zumdahl (1990)	N	N	S	N	N	N	N	N

[a] Criteria: T1: cathode rays as charged particles or waves in the ether; T2: cathode rays as ions or universal charged particles; R1: Rutherford's nuclear atom vs. Thomson's model of the atom; R2: large angle deflection vs. deflection of 1 in 20,000 particles; R3: single/compound scattering of alpha particles; B1: paradoxial stability of the Rutherford model of the atom; B2: Bohr's explanation of the hydrogen line spectrum; B3: incorporation of Planck's ideas—a deep philosophical chasm.

T = Thomson; R = Rutherford; B = Bohr; S = satisfactory; M = mention; N = No mention.

charged particles or waves in the ether (criterion T1). Again, only two textbooks described satisfactorily (S) that Thomson determined mass-to-charge ratio to decide whether cathode rays were ions or a universal charged particle (criterion T2), and the following represents a satisfactory description:

> A very striking and important observation made by Thomson is that the e/m [charge to mass] ratio does not depend on the gas inside the tube or the metal used for the cathode or anode. The fact that the e/m ratio is the same whatever gas is present in the tube proves that the cathode ray does not consist of gaseous ions, for if it did, e/m would depend on the nature of the gas. (Segal, 1989, p. 412)

Various textbooks not only did not mention the "heuristic principle" (Schwab, 1974) of Thomson's experiments (criteria T1 and T2) but also present Thomson's findings in a way that approximates to what Schwab (1962) referred to as a "rhetoric of conclusions" (cf. Brady & Holum, 1981; Hein, 1990; Masterton, Slowinski, & Stanitski, 1985; Newell, 1977; Quagliano & Vallarino, 1969; Sienko & Plane, 1971; Sisler, Dresdner, & Mooney, 1980; Stoker, 1990; Wolfe, 1988; Zumdahl, 1990).

The following three examples are presented to illustrate how some of these textbooks present scientific knowledge as a “rhetoric of conclusions”:

> Figure . . . shows that these rays travel in straight lines from the cathode. An opaque object in the tube casts a sharply defined shadow in the fluorescence at the end of the tube opposite the cathode. These cathode rays are also deflected by an electric or a magnetic field in the manner indicated by Figs . . . The conclusion drawn from these experiments and others is that *cathode rays are composed of negatively charged particles of appreciable mass.* The nature of these cathode ray particles is independent, both of the nature of the metal used for the cathode and of the nature of the residual gas in the tubes. These particles are identical with the elementary particles of electricity postulated by Stoney, viz. *electrons.* (Sisler et al. [1980], p. 152, emphasis in original)

> Scientists found that if they first pumped out much of the air in the tube, the tube glowed when a voltage was applied. Later it was found that negative particles, which were called cathode rays (electrons), passed from the negative electrode, the cathode, to the positive electrode, the anode. This and similar studies led English physicist *J. J. Thomson* (1856–1940) to propose in 1898 what is now known as the “*plum-pudding*” model of the atom. (Wolfe [1988], pp. 96–97, emphasis in original)

> A physicist in England named J. J. Thomson showed in the late 1890s that the atoms of any element can be made to emit tiny negative particles. (He knew they had a negative charge because he could show that they were repelled by the negative part of an electric field.) Thus he concluded that all types of atoms must contain these negative particles, which are now called *electrons.* (Zumdahl, [1990] p. 97, emphasis in original).

Rutherford (Criteria R1, R2, and R3)

Seven textbooks described satisfactorily (S) that Rutherford’s model of the nuclear atom had to compete with a rival framework, namely Thomson’s model of the atom (criterion R1), whereas four textbooks mentioned (M) the conflict. The following were considered to be examples of the satisfactory (S) descriptions based on criterion R1:

> In 1911 Rutherford performed the classic experiment which tested the Thomson model . . . If the positive charge and the mass are distributed evenly throughout the metal, the alpha particle has little reason to swerve off its original path . . . The Thomson model could not account for such large deflections . . . According to Rutherford, the only way to account for the large deflection is to say that the positive electricity and mass in the metal foil are concentrated in very small regions. (Sienko & Plane, 1971, p. 29)

> This was a most surprising finding [Rutherford’s alpha particle experiments] for, in Thomson’s model, the positive charge of the atom was so diffuse that the alpha particles were expected to pass through very little deflection . . . Rutherford was later able to explain the results of the scattering experiment, but he had to abandon Thomson’s idea and propose a new model for the atom. (Chang, 1981, p. 37)

Only two textbooks satisfactorily (S) described that the crucial argument in favor of Rutherford’s model was not the large angle deflections of alpha particles but rather the knowledge that 1 in 20,000 particles deflected through large angles (criterion R2). The following is an example of a satisfactory description:

> In 1911, Ernest Rutherford published the results of a series of experiments . . . For example, using a gold foil 0.00004 cm thick, he found that one alpha particle in 20,000 was deflected through an

> angle greater than 90°. From such experiments, Rutherford concluded that since most of the alpha particles pass through the foil undeflected, the volume occupied by an atom must consist largely of empty space. (Sisler et al., 1980, p. 164)

None of the textbooks described satisfactorily (S) or mentioned (M) the rivalry between two conflicting frameworks, Rutherford's hypothesis of single scattering and Thomson's hypothesis of compound scattering (criterion R3), put forward to explain Rutherford's alpha particle experiments.

As compared with Thomson's experiments, few textbooks (Newell, 1977; Quagliano & Vallarino, 1969) presented Rutherford's experiments as a "rhetoric of conclusions" (Schwab, 1962). The following is an example:

> Rutherford's experimental results indicated that the positively charged particles were concentrated in a small volume of the atom, which contained most of the mass of the atom. This small, positively charged core was called the *nucleus.* (Quagliano & Vallarino, 1969, p. 21, emphasis in original)

Bohr (Criteria B1, B2, and B3)

Four textbooks mentioned (M) that Bohr's main objective was to explain the paradoxical stability of the Rutherford model of the atom, which constituted a rival framework (criterion B1) and three textbooks described it satisfactorily (S). The following is an example of a satisfactory description:

> . . . description of the atom, which is universally accepted today, seemed very surprising and unlikely to the scientists of 1911. Why should such a structure be stable? Positive and negative charges attract one another—what keeps the negative electrons at some distance from the positive nucleus? Why aren't the electrons drawn into the nucleus as a result of the coulombic (electrostatic) attraction? Indeed, the laws of classical electromagnetic theory . . . predict unequivocally that an atom with such a structure could not exist. Nothing in classical physics can explain the existence of a stable atom with the structure elucidated by scattering experiments of Rutherford, Geiger, and Marsden. (Segal, 1989, p. 415)

None of the textbooks mentioned (M) or described satisfactorily (S) the quantization of the Rutherford model of the atom within a historical perspective (criterion B2).

Four textbooks mentioned (M) and another two described satisfactorily (S) how scientists (Bohr in this case), when faced with difficulties, often resort to contradictory ('grafts') that represent a deep philosophical chasm (criterion B3). The following is an example of a satisfactory description:

> There are two ways of proposing a new theory in science, and Bohr's work illustrates the less obvious one. One way is to amass such an amount of data that the new theory becomes obvious and self-evident to any observer. The theory then is almost a summary of the data. The other way is to make a bold new assertion that initially does not seem to follow from the data, and then to demonstrate that the consequences of this assertion, when worked out, explain many observations. With this method, a theorist says, "You may not see why, yet, but please suspend judgment on my hypothesis [cf. hard core of Lakatos, 1970] until I show you what I can do with it." Bohr's theory is of this type. Bohr said to classical physicists: "You have been misled by your physics to expect that the electron would radiate energy and spiral into the nucleus. Let us assume that it does not, and see if we can account for more observations than by assuming that it does." (Dickerson, Gray, Darensbourg, & Darensbourg, 1984, p. 264)

Once again, as compared with Thomson's experiments, few textbooks (Hein, 1990; Newell, 1977; Zumdahl, 1990) presented Bohr's work as a "rhetoric of conclusions" (Schwab, 1962). The following is an example:

> . . . Bohr constructed a model of the hydrogen atom with quantized energy levels that agreed with the hydrogen emission results we have just discussed. Bohr pictured the electron moving in circular orbits corresponding to the various allowed energy levels. He suggested that the electron could jump to a different orbit by absorbing or emitting a photon of light with exactly the correct energy content. Thus in the Bohr atom, the energy levels in the hydrogen atom represented certain allowed circular orbits. (Zumdahl, 1990, p. 337)

Evaluation Based on Additional Criteria

Table 2 presents the results of evaluation based on additional criteria, such as space (S) utilized by the textbook, mathematical (M) details, illustrations (IA) of the apparatus, and illustrations (IM) of the models.

It can be observed that, on the average, textbooks devoted about 2 pages to the work of Thomson, 1.5 pages to the work of Rutherford, and 3 pages to the work of Bohr. In the case of Thomson, 21 textbooks presented experimental details accompanied by illustrations, whereas only 2 textbooks presented mathematical details of the determination of the mass-to-charge ratio by Thomson, and

TABLE 2
Evaluation of Chemistry Textbooks Based on Space Utilized, Mathematical Details, Illustrations of Experimental Apparatus, and Models[a]

	Thomson				Rutherford				Bohr		
No.	S	M	IA	IM	S	M	IA	IM	S	M	IM
1	5	y	y	n	2	n	n	y	6	n	n
2	—	—	—	—	1	n	n	y	2	n	n
3	2.5	n	y	y	1	n	y	y	2.5	y	y
4	1	n	y	n	1	n	y	y	1.5	n	y
5	2	n	y	n	1.5	n	y	y	4	n	y
6	1	n	y	y	1.5	n	y	y	4	n	y
7	1	n	y	y	3	n	y	y	4	y	y
8	1	n	y	n	1.5	n	y	y	2	n	n
9	1.5	n	y	n	1	n	n	y	2	n	y
10	2	n	y	n	2	n	y	y	3	n	y
11	3	y	y	n	2.5	y	y	n	5.5	y	n
12	1	n	y	n	1	n	y	n	3	n	n
13	1	n	y	n	1.5	n	n	y	2	n	n
14	0.5	n	n	y	0.5	n	n	y	0.5	n	y
15	2	n	y	n	1.5	n	y	y	1	n	n
16	1	n	y	n	1	n	n	y	—	—	—
17	1.5	n	y	n	2	n	y	y	5	y	n
18	3.5	n	y	n	1.5	n	y	n	3	n	n
19	3	n	y	n	2	n	y	y	3.5	n	y
20	2.5	n	y	n	1.5	n	y	n	—	—	—
21	1	n	y	n	2	n	y	y	3	n	y
22	1	n	y	y	1.5	n	y	y	3	n	y
23	2	n	y	y	2	n	y	y	1	n	y

[a] Criteria: S = space utilized by textbook (no. of pages); M = mathematical details; IA = illustrations of experimental apparatus; IM = illustrations of models. *Note:* Textbooks are identified by a number, see Table 1; y = yes; n = no; dash indicates that the text does not deal with the subject).

6 textbooks presented illustrations of Thomson's model of the atom. It is important to note that the rationale behind the determination of the mass to charge ratio by Thomson (criterion T2) constitutes precisely the "heuristic principle" (Schwab, 1974) of Thomson's experimental work.

In the case of Rutherford, 17 textbooks presented experimental details accompanied by illustrations, whereas only 1 textbook presented mathematical details to show that the positive charge in the nucleus has a radius of about 10^{-12} cm, and 19 textbooks presented illustrations of Rutherford's model of the atom.

In the case of Bohr, only 4 textbooks presented mathematical details to derive Bohr's equation for calculating the allowed energies in a hydrogen atom, and 12 presented illustrations of Bohr's model of the atom.

These results show that textbooks tend to emphasize experimental details, perhaps at the expense of mathematical and theoretical interpretations and illustrations of the atomic models. In the case of Bohr, textbooks emphasize the experimental details of the hydrogen line spectrum and ignore Bohr's major contribution; that is, quantization of the Rutherford model of the atom (criterion B2). As one textbook put it: "Niels Bohr had tied the unseen (the interior of the atom) with the seen (the observable lines in the hydrogen spectrum)—a fantastic achievement" (Joesten, Johnson, & Netterville, 1991, p. 78). Such graphic descriptions by textbooks demonstrate how experimental findings are important, whereas the theoretical details (heuristic principles) are important only if they can furnish observable (tangible) evidence. At this stage it is of interest to note the controversy in the history of science with regard to understanding the pendulum motion, between Del Monte and Galileo (cf. Matthews, 1994, pp. 109–135). Matthews (1994) asks a very pertinent question:

> . . . why it was that the supposed isochronism of the pendulum was only seen in the sixteenth century, when thousands of people of genius and with acute powers of observation had for thousands of years been pushing children on swings, and looking at swinging lamps . . . (p. 111)

Matthews (1994) goes on to respond:

> No amount of looking will reveal isochronic motion; looking is important, but something else is required: a better appreciation of what science is and what it is aiming to do; an epistemology of science (p. 118)

This provides a clue to our dilemmma, namely how to conceptualize the role of experimental (observational) details and the "heuristic principles" (Schwab, 1974) that underlie such observations.

CONCLUSIONS: TEACHING SCIENCE AS "RHETORIC OF CONCLUSIONS" OR A PROGRESSIVE SEQUENCE OF "HEURISTIC PRINCIPLES"

Most of the textbooks seem to emphasize experimental details based on observations and generally ignore the "heuristic principles" (Schwab, 1974) that led the scientists in the first place to design their experiments and facilitated greater conceptual understanding (cf. progressive "problemshifts," Lakatos [1970]). It is important to note that very few of the textbooks present the work of Thomson, Rutherford, and Bohr within a historical framework and in general lack a philosophy of science perspective. For example, very few textbooks provide interpretations of experimental details conducive to the understanding of the following heuristic principles:

1. Thomson's experiments on cathode rays were conducted to clarify the controversy with regard to the nature of cathode rays (charged particles or waves in the ether).

2. Thomson determined mass-to-charge ratio to identify cathode rays as ions or as universal charged particles.
3. Rutherford's nuclear model of the atom had to compete with a rival framework—Thomson's "plum-pudding" model of the atom.
4. The crucial experimental finding that clinched the argument in favor of Rutherford's model was not the large angle deflection of alpha particles, but rather the knowledge that 1 in 20,000 particles deflected through large angles.
5. Rutherford's hypothesis for explaining alpha particle deflections based on single scattering had to compete with Thomson's hypothesis of compound scattering.
6. Bohr's main objective was to explain the paradoxical stability of the Rutherford model of the atom, a rival framework.
7. Bohr's major contribution was the quantization of the Rutherford model of the atom and not the explanation of the hydrogen line spectrum.
8. Bohr's incorporation of Planck's "quantum of action" represented a deep philosophical chasm.

It is plausible to suggest that textbooks should emphasize not only the experimental details but also the "heuristic principles" required to "structure inquiry" (Schwab, 1974, p. 165). The lack of an appreciation of the "heuristic principles" that underlie the experimental observations, at times (especially Thomson's work) lead the textbooks to present scientific progress as a "rhetoric of conclusions" (Schwab, 1962, p. 24). Most textbooks ignore the fact that progress in science evolves through competition between rival and conflicting frameworks, and the work of Thomson, Rutherford, and Bohr is particularly illustrative of this tentative nature of science. According to Burbules and Linn (1991): "If there is one thing that the history of science proves, it is that all theories turn out to be more or less "wrong" in the end" (p. 232). Thus, students can find textbooks more helpful if they emphasized ". . . competing frameworks of understanding that clash in the face of evidence" (p. 237).

It appears that most textbooks, by construing chemistry in the narrow sense—that is, appeal to observation and controlled experiments to test predictions—ignore the mathematical, philosophical, and metaphysical issues that could make chemistry more interesting. Musgrave (1992) questions: "Why *should* all the questions we can formulate be decidable by an observation or controlled experiment?" (p. 697, emphasis in original). It is not far fetched to suggest that most textbook authors are perhaps imbued with the positivist tradition (cf. Phillips, 1983, 1994), and textbooks reflect that philosophical stance. According to Matthews (1994), "Opposition to the mathematizing [in contrast to experimentation] of physics was a deeply held Aristotelian, and more generally empiricist, conviction" (p. 117).

Finally, an exceptional witness to the progress of science provides the following thought-provoking reflection for chemistry textbook authors, teachers, and students:

> . . . the great majority of scientific men now regard the atomic theory not only as a working hypothesis of great value but as affording a correct description of one stage of the subdivision of matter. While this is undoubtedly the case today, it is of interest to recall that less than 20 years ago there was a revolt by a limited number of scientific men against the domination of the atomic theory in chemistry. The followers of this school considered that the atomic theory should be regarded as a mere hypothesis, which was of necessity unverifiable by direct experiment, and should, therefore, not be employed as a basis of explanation of chemistry . . . This tendency advanced so far that textbooks of chemistry were written in which the word atom or molecule was taboo, and chemistry was based instead on the law of combination in multiple proportion. (Rutherford, 1915, p. 176)

This statement from Rutherford (an experimentalist *par excelence* himself) is important for two reasons: (a) it cogently illustrates the relationship between hypotheses, theories, and experimental evidence and their role in the history of the structure of the atom; and (b) it was written in 1915, long before philosophers of science presented their critique of positivist methodology.

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