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Reconstruction of the History of the Photoelectric Effect and its Implications for General Physics Textbooks

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ABSTRACT: The photoelectric effect is an important part of general physics textbooks. To study the presentation of this phenomenon, we have reconstructed six essential, history and philosophy of science (HPS)-related aspects of the events that culminated in Einstein proposing his hypothesis of lightquanta and the ensuing controversy within the scientific community. These aspects are (1) Lenard's trigger hypothesis to explain the photoelectric

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effect, (2) Einstein's quantum hypothesis to explain the photoelectric effect, (3) lack of acceptance of Einstein's quantum hypothesis in the scientific community, (4) Millikan's experimental determination of the Einstein photoelectric equation and Planck's constant, h, (5) Millikan's presuppositions about the nature of light, and (6) the historical presentation and its interpretation within a history and philosophy of science perspective. Using these aspects as criteria, we analyzed 103 university general physics textbooks. Results obtained reveal that these historical elements are largely ignored or distorted in the textbooks, with only three of the texts obtaining a score of satisfactory and none a score of excellent. It is concluded that inclusion of HPS-related aspects in general physics textbooks can facilitate a better understanding of the dynamics associated with the initial controversy and final acceptance of Einstein's explanation of the photoelectric effect by the scientific community. *Sci Ed* **94:**903–931, 2010

INTRODUCTION

The photoelectric effect constitutes an important part of the physics curriculum, and general physics textbooks consider it useful for the introduction of quantum theory. As early as 1937, Wright wrote, "Einstein's equation for the photoelectric effect . . . is the usual starting point for the presentation of quantum theory to undergraduates" (1937, p. 35). Of the 103 textbooks considered for this project, two did not include the photoelectric effect. As stated by most of the textbook authors, however, the photoelectric effect provides a good example of how a theory comes along to explain existing experimental data (blackbody radiation and the photoelectric phenomenon) that were difficult to explain and, thus, shows the heuristic power of the new theory. Despite the recognition that Einstein (1905), based on the quantum theory, provided a plausible explanation of the photoelectric effect, textbooks make no effort to clarify that Einstein's explanation of the photoelectric effect was rejected by the scientific community for nearly 20 years (cf. T. Kuhn, 1983). Although Einstein was awarded the 1921 Nobel Prize for physics to recognize, in particular, his contribution to explaining the photoelectric effect, Millikan (1924) expressed serious reservations about the lightquantum and Thomson (1925) was reluctant to accept the quantum theory. Most surprising of all was the opposition of Max Planck (founding father of the quantum theory), who withheld approval until almost 1913. Yet, this important episode in the development of current-day physics is virtually unknown to physics students, whose physics education takes place predominantly from textbooks. A practicing physicist has expressed the resulting dilemma of teachers and textbooks in eloquent terms:

> Most practicing physicists have learned what little they know of the history of this period by reading textbooks written after the quantum revolution. Often texts and teachers treat the Planck radiation law, the Einstein photoelectric equation, the Bohr atom and the Compton effect in one sequence assuming that this provides an adequate background for understanding $E = h\nu$ and $p = h\nu/c$. This can leave a student with less than total respect for the physicists who took so long to see the "obvious" necessity for this form of quantization. (Noyes, 1984, p. 95)

The main purpose of this study is to align textbook presentations with a vision of nature of science (NOS) that has been espoused by various reform documents, such as Project 2061 (American Association for the Advancement of Science [AAAS], 1993), The Pan-Canadian protocol for collaboration on school curriculum (Council of Ministers of Education, Canada, 1997), and Project Beyond 2000 (Millar & Osborne, 1998), in the United Kingdom. These documents call for the inclusion in textbooks of not only historical perspectives but also the meaningful introduction of terms, appropriate representation of key ideas, and the skillful use of models (Kesidou & Roseman, 2002). It is expected that the audience for this study would be physics textbook authors and teachers at both the freshman and high school levels, who would apply the concepts presented herein at the appropriate levels of complexity.

On the basis of these considerations, the authors set out to study the available introductory physics textbooks to establish the magnitude of the problem. The research project was designed to meet the following objectives:

1. An historical reconstruction of the events that culminated in Einstein proposing his hypothesis of light quanta to explain the photoelectric effect and the ensuing controversy within the scientific community.
2. Elaboration of six criteria for evaluating textbooks based on the historical reconstruction of the photoelectric effect.
3. Evaluation of introductory university-level general physics textbooks based on the six criteria.

The subsequent sections follow the listed objectives for the study. We begin, however, with a review of analyses of textbooks based on a history and philosophy of science (HPS) perspective. We summarize the pertinent literature associated with the Thomson–Rutherford controversy and the Millikan–Ehrenhaft controversy and then focus on textbook studies that address, more generally, NOS issues.

REVIEW OF TEXTBOOK STUDIES BASED ON A HISTORY AND PHILOSOPHY OF SCIENCE PERSPECTIVE

The Thomson–Rutherford controversy in regard to single/compound scattering of alpha particles is the subject of textbook analyses by Niaz (1998) and Rodríguez and Niaz (2004a). We begin with a brief summary of the historical context. Both E. Rutherford (1911) and J. J. Thomson performed similar experiments on the scattering of alpha particles, but their interpretations were entirely different. Thomson propounded the hypothesis of *compound scattering*, according to which a large angle deflection of an alpha particle resulted from successive collisions between the alpha particles and the positive charges distributed throughout the atom. Rutherford, in contrast, propounded the hypothesis of *single scattering*, according to which a large angle deflection resulted from a single collision between the alpha particle and the massive positive charge in the nucleus. The rivalry led to a bitter dispute between the proponents of the two hypotheses (Wilson 1983). Rutherford's dilemma was that he was entirely convinced and optimistic that his model of the atom provided a better explanation of experimental findings, and yet it seems that the prestige, authority, and even perhaps some reverence for his teacher (Thomson) made him waver in his conviction. A science student may wonder why Thomson and Rutherford did not meet over dinner (they were well known to each other) and decide in favor of one or the other model. Progress in science is, however, much more complex. Both, Thomson and Rutherford, stuck to their presuppositions. These issues, if discussed in class and textbooks, could make the presentation of science much more human and attractive. Niaz (1998) has reported that of the 23 general chemistry textbooks analyzed none satisfactorily described or mentioned this controversy. Rodríguez and Niaz (2004a) have reported that of the 41 general physics textbooks they analyzed, 2 offered satisfactory descriptions and 2 made a simple mention. All textbooks analyzed were published in the United States.

The Millikan–Ehrenhaft controversy and determination of the elementary electrical charge is the subject of textbook analyses by Niaz (2000) and Rodríguez and Niaz (2004b). We first present a brief summary of the context. A historical reconstruction of the oil drop experiment that led to the determination of the elementary electrical charge (e) shows the controversial nature of the experiment and the difficulty one has performing the experiment even today (Holton, 1978; Jones, 1995; Klassen, 2009a; Niaz, 2005). Despite these problems, most chemistry and physics textbooks consider the oil drop experiment to be a simple, classic, and beautiful experiment, in which Robert A. Millikan (1868–1953), by an exact experimental technique, determined the elementary electrical charge. Robert Millikan and Felix Ehrenhaft obtained very similar experimental data, and still Millikan postulated the existence of the electron (universal charged particle) and Ehrenhaft the existence of subelectrons (fractional charges). A bitter dispute ensued between the rival contenders that lasted for many years (1910–1925). Niaz (2000) has reported that of the 31 general chemistry textbooks he analyzed none mentioned the Millikan–Ehrenhaft controversy. Similarly, Rodríguez and Niaz (2004b) have reported that not one of the 43 general physics textbooks analyzed in their study mentioned the controversy. Some textbooks explicitly denied that the drops studied by Millikan had fractional charges, i.e., a charge unequal to an integer times the electron charge. All textbooks analyzed were published in the United States.

Leite (2002) analyzed five high school physics textbooks published in Portugal on criteria such as historical experiments, analyses of data from historical experiments, integration of historical references within the text, use of original historical sources, evolution of science, and sociopolitical context in scientific research, among others. Leite concluded that the historical content included in the textbooks hardly provided students with an adequate image of science and the work of the scientists.

Justi and Gilbert (1999) analyzed high school chemistry textbooks (nine from Brazil and three from the United Kingdom) to study the presentation of atomic models. These authors report the use of hybrid models based on various historical developments, such as Ancient Greek, Dalton, Thomson, Rutherford, Bohr, and quantum mechanics (Schrödinger's equation). In concluding they state, "Hybrid models, by their very nature as composites drawn from several distinct historical models, do not allow the history and philosophy of science to make a full contribution to science education" (p. 993).

As shown by an historical reconstruction, it was the acceptance of the atomic-molecular theory that facilitated an understanding of "amount of substance" and its unit the "mole" (Padilla & Furio-Mas, 2008). However, in a study based on 30 general chemistry textbooks (published in the United States), these authors found that a majority of the textbooks present an ahistoric and aproblematic interpretation of this topic.

Abd-El-Khalick, Waters, and Le (2008) have drawn attention to the importance of including nature of science (NOS) in high school chemistry textbooks. These authors analyzed 14 textbooks, including five "series" spanning one to four decades, with respect to the following NOS aspects: empirical, tentative, inferential, creative, theory driven, myth of the scientific method, nature of scientific theories and laws, and the social and cultural embeddedness of science. Results from this study revealed that chemistry textbooks fared poorly in their representation of NOS, which led the authors to conclude, "These trends are incommensurate with the discourse in national and international science education reform documents . . . " (p. 835).

On the basis of content analysis of school chemistry textbooks and syllabi, Van Berkel, DeVos, Verdonk, and Pilot (2000) have identified the dominant school chemistry as a form of normal science education (NSE), which is in turn based on Kuhn's "normal science." These authors have characterized NSE as being dangerous in that it isolates the learner from the history and philosophy of science and, as such, is narrow and rigid and tends to instill a dogmatic attitude toward science.

Given these antecedents of textbook analyses based on a history and philosophy of science perspective, it would be interesting for science educators to see how general physics textbooks present the photoelectric effect within a HPS perspective.

RECONSTRUCTION OF THE HISTORY OF THE PHOTOELECTRIC EFFECT

Throughout the second half of the 19th century, light was considered to be a wave propagating in an all-pervading medium. Properties such as diffraction, interference, and polarization convinced physicists that visible monochromatic light is a periodic transverse oscillation. Between 1898 and 1912, a majority of physicists thought that x-rays were impulses propagating through the electromagnetic field, and this was considered to be compatible with the wave theory of light. The photoelectric effect is generally considered to be a byproduct of Hertz's (1887) experimental demonstration of electromagnetic waves. Hertz (1883) had previously shown that cathode rays were a type of wave in the ether similar to light. Later, Thomson (1897) conclusively showed that cathode rays consisted of charged particles (electrons). By 1889 (2 years after its discovery by Hertz), the photoelectric effect had assumed a special significance for many scientists in different parts of Europe and consisted primarily of the following observation: illuminating a metal plate with ultraviolet light initiates a flow of negatively charged particles from the plate. The nature of the photoelectric current was not clear and led to considerable controversy.

Philipp Lenard's Triggering Hypothesis

Lenard (1902) was an acknowledged expert on cathode rays and generally agreed with Hertz (with whom he had worked as an assistant) that both cathode rays and x-rays were ether waves. Starting in 1902, Lenard conducted important experiments on the photoelectric effect and his contribution has been summarized by Wheaton (1983) in the following terms:

> He [Lenard] uncovered the surprising fact that the maximum velocity with which electrons are ejected by ultraviolet light is entirely independent of the intensity of light. This result convinced him that there could be no transformation of light energy into electron kinetic energy. Instead, he proposed that electrons in an atom *already* possess their photoelectric velocity, or the potential energy equivalent, by virtue of their membership in the atomic system. The light only triggers the release of selected electrons; it does not add energy to them. Until 1911 this *triggering hypothesis* formed the basis of almost all physicists' understanding of the photoelectric effect. (pp. 74–75, italics in original)

A major criticism of the triggering hypothesis was due to the absence of an influence of temperature on the photoelectric effect, "If the electron takes its velocity from within the atom, heating the cathode should increase the speed of the emitted electrons. Tests failed to find the increase" (Wheaton, 1978, p. 320). Among others, Millikan and Winchester (1907) failed to find any variation of the photoelectric effect with temperature.

Albert Einstein's Hypothesis of Lightquanta

Einstein (1905) proposed that ordinary light behaves as though it consists of a stream of independent localized units of energy that he called *lightquanta*. He was led to this revolutionary view by a statistical analysis of the properties of an idealized sample of radiation in thermodynamic equilibrium. His suggestion of this hypothesis arose from the close analogy he perceived between the behavior of radiation and the behavior of a gas (Wheaton, 1983, p. 106). According to Einstein, if light consists of localized quanta of energy, an electron in an atom will receive energy from only one lightquantum at a time. Monochromatic light of frequency ν can, therefore, grant electrons only energy, $h\nu$, where h is Planck's constant. If some small part p of that energy must be used to release the electron from the metal itself, all electrons of charge e so released will be stopped by a decelerating potential P, following the relation:

$$\tfrac{1}{2}mv^2 = Pe = h\nu - p \tag{1}$$

(where $\frac{1}{2}mv^2$ is the maximum kinetic energy of the ejected electrons). Einstein's (1905) prediction that the stopping potential "should be a linear function of the frequency of the incident light, when plotted in Cartesian coordinates, and its slope should be independent of the nature of the substance investigated" (p. 146, English translation from Jammer, 1966, p. 35) became the cornerstone of Millikan's research program. Interestingly, Einstein's hypothesis also explained Lenard's triggering hypothesis, viz., the maximum velocity of photoelectrons must be independent of the intensity of light, and the energy received by an electron depends on the frequency. According to Wheaton (1983),

> Einstein's hypothesis of lightquanta was not taken seriously by mathematically adept physicists for just over fifteen years. The reasons are clear. It seemed to be an unnecessary rejection of the highly verified classical theory of radiation... How lightquanta could possibly explain interference phenomena was always the central objection. (p. 109)

In other words, Lenard's triggering hypothesis (and its quantum analog by Planck) and Einstein's quantum hypothesis constituted rival hypotheses to explain the same experimental (photoelectric) phenomenon. It is, however, plausible to suggest that Einstein's quantum hypothesis explained more experimental facts than Lenard's trigger hypothesis, and this constitutes additional heuristic power (Lakatos, 1970).

Max Planck's Alternative Interpretation of the Hypothesis of Lightquanta

Planck is generally considered to be the originator of the quantum hypothesis. "From 1900 to 1905 Planck's radiation formula was generally considered to be neither more nor less than a successful representation of the data" (Pais, 1982, p. 374). There is, however, some controversy with respect to this claim as, for example, T. Kuhn (1978) considered that it was not Planck but Einstein (1905) who started the quantum revolution.

Planck (1913) attempted to interpret the photoelectric effect by suggesting that light energy is not transformed into electron kinetic energy; the latter already exists within the atom. According to Wheaton (1983): "Planck's theory was the quantum analog of the triggering hypothesis" (p. 179) and thus suffered most of its drawbacks. Planck's outlook becomes even more clear from the letter sent by Planck, Rubens, Nernst, and Warburg to the Kulturminister in their attempt to have the non-German Einstein appointed to the Kaiser Wilhelm Gesellschaft and the Prussian Academy of Sciences on June 12, 1913, which stated,

> That [Einstein] may occasionally have missed the mark in his speculations, as for example with his hypothesis of lightquanta, ought not be held too much against him, for it is impossible to introduce new ideas, even in the exact sciences, without taking risk. (Quoted in Kahan, *Archives internationales d'histoire des sciences, 15*, 337–342, 1962. Reproduced in Wheaton, 1983, p. 194)

Jammer (1966, pp. 43–44) also reproduces this letter with a slightly different translation and considers it to be an important document as it puts on record the reaction toward Einstein's hypothesis of lightquanta prior to Millikan's experimental determination of

Planck's constant (h). Teachers and textbooks may want to reflect upon the difficulties faced in envisioning new horizons and the role played by "speculations" and "risks" even in the "exact sciences."

Millikan's Experimental Determination of Planck's Constant (*h*)

Starting around 1904, Millikan devoted considerable effort to the experimental determination of Einstein's photoelectric equation (see Equation (1)) and, as a consequence, calculated the experimental value of Planck's constant h (Millikan, 1913a, 1913b, 1914, 1915, 1916a, 1916b). Millikan's value for h (6.57×10^{-27} erg s) came quite close to that reported by Planck (6.55×10^{-27}). Millikan was quite satisfied with all the technical innovations that he developed for his experimental measurements and concluded "... so far as experiment has now gone, Einstein's photoelectric equation, whatever may be said of its origin, seems to stand up accurately under all of the tests to which it has been subjected" (Millikan, 1916a, p. 31). Later critical evaluation of Millikan's experimental determinations also recognized its importance: "... Millikan's results were never questioned, and were quickly recognized by leading European physicists to be definitive. But acceptance of the Einstein law of the photoelectric effect did not carry with it acceptance of the hypothetical lightquantum" (Wheaton, 1983, p. 241).

Millikan's Interpretation of Einstein's Hypothesis of Lightquanta

Given Millikan's penchant for controversy (cf. oil drop experiment; Holton, 1978, Niaz, 2000, 2005), it is interesting to note that in the same publication (Millikan, 1916b), he recognized the validity of the Einstein photoelectric equation and simultaneously questioned the underlying hypothesis of lightquanta: "Despite then the apparently complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it. But how else can the equation be obtained?" (Millikan, 1916b, p. 384). This may sound incredulous to any student of history and philosophy of science. Actually, Millikan went far beyond doubting Einstein's own development since 1905 (Einstein having restated his thesis in 1916), and it is worthwhile to follow Millikan's train of thought in some detail:

> It was in 1905 that Einstein made the first coupling of photo effects and with any form of quantum theory by bringing forward the bold, not to say *the reckless, hypothesis* of an electro-magnetic light corpuscle of energy $h\nu$, which was transferred upon absorption to an electron. This hypothesis may well be called reckless first because an electromagnetic disturbance which remains localized in space seems a violation of the very conception of an electromagnetic disturbance, and second because it flies in the face of the *thoroughly established facts of interference*. The hypothesis was apparently made solely because it furnished a ready explanation of one of the most remarkable facts brought to light by recent investigations, viz., that the energy with which an electron is thrown out of a metal by ultraviolet light or X-rays is independent of the intensity of the light while it depends on its frequency. This fact alone seems to demand *some modification of classical theory* or, at any rate, it has *not yet been interpreted satisfactorily in terms of classical theory*. (Millikan, 1916b, p. 355, italics added)

It is not far-fetched to suggest that Millikan's train of thought could be understood along the following lines: We have thoroughly established facts of interference based on the classical wave theory → although, some modification of classical theory may be necessary → nevertheless, Einstein's hypothesis of lightquanta is reckless. Later, more evidence will be provided to substantiate this suggestion.

Millikan was awarded the 1923 Nobel Prize in physics for his contributions to the experimental determination of both the elementary electrical charge and Planck's constant based on the Einstein photoelectric equation. In his acceptance speech delivered on May 23, 1924, Millikan recounted the difficulties during the experiments and concluded on a pessimistic note:

> ... the conception of *localized* light-quanta out of which Einstein got his equation must still be regarded as far from being established ... until it [hypothesis of lightquanta] can account for the facts of interference and the other effects which have seemed thus far to be irreconcilable with it, we must withhold our full assent. Possibly the recent steps taken by Duane, Compton, Epstein and Ehrenfest may ultimately bear fruit in bringing even interference under the control of localized light-quanta. *But as yet the path is dark.* (Millikan, 1965, p. 63 and 65)

Millikan's Interpretation of the Hypothesis of Lightquanta in Retrospect

In a recent study, Holton (1999) has asked a very pertinent question: "So Millikan's (1916b) paper is not at all, as we might now naturally consider it to be, an experimental proof of the quantum theory of light" (p. 232). This statement has important implications. The 1916 publication was considered by its own author as an experimental test of Einstein's photoelectric equation and in no way a confirmation of the underlying hypothesis of lightquanta (Millikan, 1916b). On the contrary, most textbooks and physicists at present would consider Millikan's (1916b) experimental data as evidence for Einstein's quantum theory (hypothesis of lightquanta). To make things even more difficult, some scholars consider that Einstein, not Planck, was the originator of the quantum hypothesis (Brush, 2000; T. Kuhn, 1978; Wheaton, 1983). How is one to resolve this dilemma? A plausible explanation is provided by Millikan's commitment to his presuppositions with respect to the wave theory of light stated quite explicitly in many articles (Millikan, 1916a, 1916b, 1965). The degree to which Millikan adhered to the wave theory of light is corroborated by the following scholars:

a. According to Wheaton (1983), "Despite his uncontested proof of Einstein's linear photoeffect relation, Millikan never doubted, until 1922, that an explanation of the result would be found without the suspect lightquantum. His particularly strong opposition may be attributed both to his respect for European mathematical physics—he had studied under Planck and Nernst in Berlin—and to the tradition that his teacher, Albert Michelson, had developed in American precision measurement in wave optics" (pp. 258–259).
b. Holton (1999) describes Millikan's presupposition in truly picturesque terms: "What we now refer to as the photon was, in Millikan's view, a 'bold, not to say the reckless, hypothesis'—reckless both because it was contrary to such classical concepts as light being a wave propagation phenomenon, and because of the 'facts of interference' ... In the background we glimpse the presence of Michelson, the 'Artist of Light,' who was Millikan's admired patron and colleague at the Ryerson Laboratory, the 1907 Nobelist, famous for his interferometers, the work carried out with their aid—and for his adherence to ether physics to his death in 1931" (p. 232).

It is clear from the historical record that theories of the photoelectric effect, beginning with Lenard's triggering hypothesis, existed before Einstein proposed his light quantum. Among the most prominent physicists not to accept Einstein's theory for some time were Max Planck and Robert Millikan. Millikan, although he was able to demonstrate Einstein's equation experimentally with a high degree of precision, did not accept the quantum hypothesis until much later. Interestingly, Millikan (1950) in his autobiography, written at the age of 82, even tried to "rewrite" history to make his account more in tune with the unfolding of historical events after 1924 (for details, see Niaz, 2009, chap. 8). We see that the experimental findings relating to the photoelectric effect were interpreted in multiple ways, depending on the theoretical frameworks of the scientists involved. The historical reconstruction that we have outlined serves as the basis for our "measuring stick" against which to place the presentations of the photoelectric effect in introductory university-level physics textbooks. It is not our intention to equate the amount of historical detail with the level of pedagogical benefit of the textbook. Nevertheless, some degree of historical detail in our presentation is necessary in order to provide teachers and textbook authors with sufficient background to convince them of the advisability of our approach. In applying our guidelines, some of the details can be removed, modified, or changed depending on the nature/level of the course and students' interest/background.

CRITERIA FOR EVALUATION OF GENERAL PHYSICS TEXTBOOKS

The study was carried out in a physics department, and textbooks were obtained from the personal libraries of various members of the department; see Appendix A for a list of textbooks used.

The following ratings were used to evaluate the textbooks: Excellent (E), Satisfactory (S), Mention (M), and No mention (N). Textbooks were awarded the following points: Excellent (E) = 3 points, Satisfactory (S) = 2 points, Mention (M) = 1 point, and No mention (N) = 0 point. On the basis of the historical reconstruction of the photoelectric effect presented in the previous section, the researchers formulated the following criteria for the evaluation of general physics textbooks:

1. *Lenard's trigger hypothesis to explain the photoelectric effect* (C1). Lenard made the important experimental determination that in photoelectric phenomena the velocity of the ejected electrons is independent of the intensity of light. According to his trigger hypothesis, electrons in an atom already have the necessary potential energy, and the incident light only triggers the release of the selected electrons. This criterion is based on Lenard (1902) and Wheaton (1983). For this criterion to be met, it is important for the textbooks to describe the following aspects:

   a. Lenard in 1902 strongly believed in the wave theory of light.
   b. Velocity of the ejected electrons was independent of the intensity of light.
   c. Electrons in an atom already had the necessary potential energy.
   d. Incident light only triggers the release of the selected electrons.

   The ratings were applied in the following way:
   Excellent: Description of aspects (a), (b), (c), and (d), with sufficient elaboration.
   Satisfactory: Aspect (a) and two other aspects with adequate elaboration.
   Mention: Any one or two aspects with some elaboration.
   No mention: None of the four aspects.

2. *Einstein's quantum hypothesis to explain the photoelectric effect* (C2). According to Einstein, if light consists of localized quanta of energy, an electron in an atom will receive energy from only one lightquantum at a time. On the basis of this hypothesis, Einstein predicted that the stopping potential, when plotted against the frequency of the incident light, would give a straight line whose slope would provide Planck's constant, h. Furthermore, Einstein's hypothesis constituted a rival explanation to Lenard's triggering hypothesis to explain the photoelectric effect. This criterion is based on Einstein (1905), Holton (1999), and Wheaton (1983). For this criterion to be met, it is important for the textbooks to describe the following aspects:

    a. Einstein's quantum hypothesis constituted a rival to Lenard's trigger hypothesis.
    b. Einstein explained the finding that the velocity of ejected electrons would depend on the frequency and not the intensity of incident light.
    c. Light consists of localized quanta of energy, so an electron in an atom will receive energy from only one photon at a time.
    d. Einstein predicted that a plot of the stopping potential against frequency would yield a straight line whose slope would provide Planck's constant, h.

    The ratings were applied in the following way:
    Excellent: Description of aspect (a) along with any other aspect, with sufficient elaboration.
    Satisfactory: Any three aspects, except (a) with adequate elaboration.
    Mention: Any two aspects, except (a) with some elaboration.
    No mention: One or none of the four aspects.
3. *Lack of acceptance of Einstein's quantum hypothesis in the scientific community* (C3). Although Einstein presented his interpretation of the photoelectric effect based on the quantum hypothesis in 1905, it was generally rejected by the scientific community. The main objection against Einstein's hypothesis was that it seemed to refute the highly accepted classical wave theory of light. Even Planck, the "originator" of the quantum theory, opposed Einstein's hypothesis until about 1913. It took many years for this "revolutionary theory" to be accepted in the body of scientific knowledge. This criterion is based on Einstein (1905) and Wheaton (1983). For this criterion to be met, it is important for the textbooks to describe the following aspects:

    a. Truly novel ideas are generally accepted very slowly.
    b. Einstein's hypothesis was not accepted by the scientific community, including Planck the "originator" of the quantum hypothesis, for many years.
    c. The main objection to Einstein's hypothesis was that it seemed to refute the highly accepted classical wave theory of light.

    The ratings were applied in the following way:
    Excellent: Description of aspects (a), (b), and (c) with sufficient elaboration.
    Satisfactory: Aspects (b) and (c) with adequate elaboration.
    Mention: Aspect (b) or (c) with some elaboration.
    No mention: None of the three aspects.
4. *Millikan's experimental determination of the Einstein photoelectric equation and Planck's constant, h* (C4). Millikan provided the first direct experimental proof of the exact validity of the Einstein equation ($\frac{1}{2}mv^2 = Pe = h\nu - p$) and the first direct photoelectric determination of Planck's constant, h. According to Holton (1999),

"Ironically, it had been Millikan's experiment (Millikan, 1916b) which convinced the experimentalist-inclined committee in Stockholm to admit Einstein to that select circle [Nobel Prize]" (p. 235). For this criterion to be met, it is important for the textbooks to describe the following aspects:

a. Underdetermination of scientific theories by experimental evidence, viz., no amount of experimental evidence can provide conclusive proof for a theory.
b. Experimental details of Millikan's determination of Einstein's photoelectric equation and Planck's constant h.
c. The graph of stopping potential against frequency, whose slope would provide Planck's constant, h.

The ratings were applied in the following way:
Excellent: Description of aspect (a) and one other aspect with sufficient elaboration.
Satisfactory: Aspects (b) and (c) with adequate elaboration.
Mention: Aspect (b) or (c) with some elaboration.
No mention: None of the three aspects.

5. *Millikan's presuppositions about the nature of light* (C5). Although Millikan provided the first experimental proof of Einstein's equation, he considered Einstein's interpretation of the photoelectric effect, based on the quantum hypothesis, as "the reckless, hypothesis" (Millikan, 1916b, p. 355). Millikan's opposition to the quantum hypothesis is attributed to his prior presupposition and a strong belief in the classical wave theory of light. This shows the contradictory and inconsistent nature of Millikan's contribution. This criterion is based on Holton (1999), Millikan (1916b), and Wheaton (1983). For this criterion to be met, it is important for the textbooks to describe the following aspects:

a. Before doing an experiment, scientists invariably do have prior theoretical beliefs or presuppositions and they resist any change in those epistemological beliefs.
b. In the present case, Millikan strongly believed in the wave theory of light.
c. Millikan (1916b) presented experimental evidence to support Einstein's photoelectric equation and in the same paper considered his underlying hypothesis to be, "... the bold, not to say the reckless hypothesis ... "

The ratings were applied in the following way:
Excellent: Description of aspects (a), (b), and (c) with sufficient elaboration.
Satisfactory: Aspects (a) and (b) with adequate elaboration.
Mention: Aspects (b) and (c) with some elaboration.
No mention: None of the three aspects.

6. *The historical record presented and its interpretation within a history and philosophy of science perspective* (C6). An historical reconstruction of the photoelectric shows that it is based on a series of experimental findings intertwined with their interpretations based on different theoretical frameworks. To facilitate a better understanding of the photoelectric effect, it is essential that the textbooks are consistent in attributing the different experimental findings and their interpretations to the relevant scientists. For example, Millikan accepted Einstein's equation but not his interpretation. Textbooks tend to confound the issues by attributing to Millikan the acceptance of both. This criterion is strictly based on the historical record and may give extra points to textbooks that do represent the historical part well. Most textbooks would perhaps

mention Einstein's hypothesis and Millikan's experimental determination; thus, to classify as Mention (M), textbooks need to make an extra effort of including one more aspect. For this criterion to be met, it is important for the textbooks to describe the following aspects:

a. Lenard's experimental findings and his trigger hypothesis.
b. Einstein's hypothesis to explain the photoelectric effect.
c. Opposition to the acceptance of Einstein's hypothesis in the scientific community.
d. Millikan's experimental determination to provide evidence for Einstein's equation and the determination of h.
e. Millikan's presuppositions that led him to reject Einstein's quantum hypothesis.

The ratings were applied in the following way:
Excellent: Description of all five aspects of the historical record with sufficient elaboration.
Satisfactory: Any four aspects, including (e) with adequate elaboration.
Mention: Any three aspects with some elaboration.
No mention: None, or any one or two of the five aspects.

Procedure for Applying the Criteria

Before analyzing the textbooks, all four authors familiarized themselves with the historical reconstruction of the photoelectric effect. Furthermore, all four had a similar epistemological framework with respect to various philosophical questions, such as the role of presuppositions in scientific progress, theory-ladenness of observations, and the underdetermination of scientific theories by experimental evidence. It is plausible to suggest that a different historical reconstruction may emphasize different aspects and, thus, elaborate a different set of criteria. Our study, based on the aforementioned criteria, is one attempt to improve the presentation of the photoelectric effect and we do not rule out other attempts with different warrants. We also believe that these epistemological questions provide for a historical perspective called for in the curriculum frameworks and that the history of the photoelectric effect provides for a rich context. Initially 9 textbooks from a total of 103 were analyzed for validation of the criteria (see Appendix B). Elaboration of the six criteria was a collaborative exercise, which went through various stages of revision and refinement. Validation of the criteria was completed in five stages (see Appendix B for details). In each of the stages, the four authors first analyzed the textbooks separately and then compared their evaluations. All differences were resolved by discussion, and a final classification was reached by consensus on the six criteria and on each of the nine textbooks analyzed. It was observed that Criteria 1 and 2 required more discussion. On Criterion 1, the discussion centered on the need to attribute all four aspects to Lenard's trigger hypothesis, especially aspect (b), which referred to the fact that the velocity of the ejected electrons was independent of the intensity of light. On Criterion 2, the discussion centered on the need to recognize that Einstein's quantum hypothesis constituted a rival to Lenard's trigger hypothesis, the relationship between the velocity of ejected electrons and both the frequency and the intensity of incident light, and Einstein's prediction as to how the value of Planck's constant, h, could be determined. As the validation process progressed through the five stages, the intercoder agreement increased and reached 100% on all six criteria (see Appendix B). This process also helped to elaborate the different aspects (codes) based on the criteria to apply to the actual text. In each of the criteria, we started with a tentative list of these codes based on the historical reconstruction. As we progressed through the five stages of validation (Appendix B), these were then discussed, revised, and refined, so as to achieve consensus. This process was based on the analyses of nine textbooks, which went through five stages over a period of 11 days. We illustrate our procedure with an example from Criterion 3, which dealt with *Lack of acceptance of Einstein's quantum hypothesis in the scientific community*, and required three aspects (a, b, and c) for a code of excellent. It was our expectation that at least some textbooks might refer to aspect (a), viz., *Truly novel ideas are generally accepted very slowly*, as part of everyday knowledge or even perhaps common sense. Thus a code of excellent must require the remaining two aspects (b and c). Criterion 4, by way of contrast, dealt with *Millikan's experimental determination of the Einstein photoelectric equation and Planck's constant, h.* To have a code of excellent on this criterion, the following aspect (a) was essential: *Underdeterimination of scientific theories by experimental evidence, viz., no amount experimental evidence can provide conclusive proof for a theory*. Most science educators familiar with HPS would agree that this aspect is counterintuitive for most teachers and textbook authors. Consequently, we reasoned that if a textbook dealt with aspect (a) it could be classified as excellent with only one additional aspect (b or c). Results obtained do support our reasoning and expectations: On Criterion 3, at least three textbooks got a code of excellent, whereas on Criterion 4, none got excellent.

It is important to note that intercoder reliability estimates are essential but not extant from controversy. For example, in textbook analyses that depend on counting the number of figures, diagrams, and tables, intercoder agreement is high and free of disagreements. However, in the present study, evaluation of the textbooks is based on philosophical and epistemological issues that pertain to competing paradigms and, hence, generate considerable discussion (for further elaboration of this aspect, cf. Chiappetta, Ganesh, Lee, & Phillips, 2006).

EVALUATION OF GENERAL PHYSICS TEXTBOOKS: RESULTS AND DISCUSSION

In evaluating 103 textbooks, the tasks were simplified due to the fact that most of the textbooks were largely deficient of any material on most of the criteria. Despite not approaching the photoelectric effect in an overall satisfactory manner from the point of view of our six criteria, some textbooks did offer good incidental insights. Several pointed out that "[h]ow the photoelectric effect was discovered was an irony of history" (Weidner & Browne, 1985, p. 867). Dull, Metcalfe, and Williams (1964, as in Appendix A) elaborate on this point:

> In 1889 Hertz stated, "The wave theory of light is, from the point of view of human beings, a certainty." Ironically, it was Hertz who was soon to discover a most important phenomenon [the photoelectric effect] in connection with the absorption of light, one which would create a dilemma and at the same time set the stage for the *new physics* that was to emerge in the early years of the twentieth century. (Italics in original, p. 333)

Several textbooks comment on the extraordinary nature of Einstein's insight into the photoelectric effect made possible by his "invention" of the lightquantum. Borowitz and Bornstein (1968) remark that "In the same year that he proposed the special theory of relativity, Einstein solved the riddle of the photoelectric effect in every detail. His theory is characteristically beautiful in its simplicity" (p. 650). McGervey (1983) writes that

> In 1905 (when most people either had not heard of Planck's theory, or, having heard of it, did not believe it), Einstein made a logical generalization. He wrote: "According to the assumption considered here, the spreading of a light beam emanating from a point source does not cause the energy to be distributed continuously over larger and larger volumes, but rather the energy consists of a finite number of energy quanta, localized at space points, which move without breaking up and which can be absorbed or emitted only as wholes" (Footnote: A. Einstein, *Ann. Phys. (Leipzig)* **17**, 132–148 (1905). Translated by J. McGervey). Einstein was not engaging in mere idle speculation; he went on to suggest that consequences of this property of light should be observed in the photoelectric effect, . . . (pp. 73–74)

If an overall characteristic of the 103 textbooks could be identified, it might be the sporadic nature of the inclusion of the relevant historical information. For most, but not all authors, the historical aspect seems not to have been part of an overall writing strategy. In many instances, it was a challenge to construct a satisfactory solution to a particular criterion by piecing together passages from various places in the relevant section.

In the following sections, we outline and provide detail of our analysis of the textbooks on the six criteria.

Criterion C1: Lenard's Trigger Hypothesis to Explain the Photoelectric Effect

Only 16 textbooks mention Lenard's experimental findings, and none of them can be categorized as either satisfactory or excellent (see Tables 1 and 2). The only aspect mentioned is Criterion 1(b), namely, that the velocity of the ejected electrons is independent of the intensity of light. For example, Radin and Folk (1982) write that ". . . in 1902, Lenard made the astonishing discovery that *the kinetic energies of the emitted electrons were altogether independent of the intensity of light*" (italics in original, p. 764). Similarly, Serway and Faughn (1995) write that "1902 Philip Lenard found that the maximum kinetic energy of photoelectrons (electrons emitted by light) does not depend on the intensity of the incoming radiation. Although he was unable to establish the precise relationship, Lenard found that the maximum kinetic energy increases with light frequency" (p. 702). Typical of many of the books, Serway and Faughn go on to write that "[t]he lack of dependence on intensity was completely unexpected and could not be explained by classical physics" (p. 702), ignoring the historical fact that theories of the day, like Lenard's trigger hypothesis, were considered perfectly adequate to explain the phenomenon. Not one of the textbooks refers in any manner to Lenard's trigger hypothesis.

Criterion C2: Einstein's Quantum Hypothesis to Explain the Photoelectric Effect

Of the six criteria, Criterion 2 has the best score (see Tables 1 and 2). However, no textbook achieved a score of excellent owing to the complete absence of any reference to the trigger theory of the photoelectric effect. A particularly good example of a satisfactory treatment is provided by Hecht (2003), and segments of the section labeled "Einstein and the Photon" are quoted here:

> Einstein's first paper on light-quanta, "On a Heuristic View Concerning the Generation and Conversion of Light," was published in 1905 (before Relativity). Heuristic means something that serves as a guide in the solution of a problem but is otherwise itself unproved. In that

TABLE 1
Evaluation of Physics Textbooks Based On a Reconstruction of the History of the Photoelectric Effect

		Criteria/Score[a,b]						
No.	Textbook	C1	C2	C3	C4	C5	C6	Total Score[c]
1	Acosta, Cowan, and Graham (1973)	M	M	N	M	N	N	3
2	Arfken et al. (1989)	N	M	N	M	N	N	2
3	Atkins (1976)	N	M	N	N	N	N	1
4	Atkins (1965)	N	M	N	N	N	N	1
5	Beiser (1991)	N	S	N	N	N	N	2
6	Beiser (1979)	N	S	N	N	N	N	2
7	Blackwood and Kelly (1955)	N	N	N	N	N	N	0
8	Blanchard et al. (1958)	N	N	N	N	N	N	0
9	Borowitz and Bornstein (1968)	N	S	M	N	N	N	3
10	Bueche (1986)	N	M	N	N	N	N	1
11	Bueche (1980)	N	M	N	N	N	N	1
12	Bueche (1977)	N	M	N	N	N	N	1
13	Bueche (1975)	N	N	N	N	N	N	0
14	Bueche (1969)	N	M	N	N	N	N	1
15	Bueche (1965)	N	N	M	N	N	N	1
16	Bueche and Wallach (1994)	N	M	N	N	N	N	1
17	Coletta (1995)	N	M	N	N	N	N	1
18	Cooper (1992)	N	M	M	N	N	N	2
19	Cooper (1968)	N	M	M	N	N	N	2
20	Copeland and Bennett (1961)	M	M	N	N	N	N	2
21	Cutnell and Johnson (2007)	N	N	N	N	N	N	0
22	Dull, Metcalfe, and Williams (1964)	N	M	N	M	N	N	2
23	Durbin (1955)	N	N	N	N	N	N	0
24	Eisberg and Lerner (1981)	N	S	S	S	N	N	6
25	Fishbane et al. (2005)	N	N	N	N	N	N	0
26	Fishbane et al. (1993)	N	M	N	N	N	N	1
27	Gamow and Cleveland (1960)	N	M	N	N	N	N	1
28	Gettys, Keller, and Skove (1989)	N	M	N	M	N	N	2
29	Giancoli (1998)	N	S	N	N	N	N	2
30	Giancoli (1984)	N	S	N	N	N	N	2
31	Greenberg (1978)	N	M	N	N	N	N	1
32	Greene (1962)	N	M	N	N	N	N	1
33	Hagelberg (1973)	N	M	N	S	N	N	3
34	Halliday and Resnick (1981)	N	S	E	M	S	M	9
35	Halliday and Resnick (1974)	N	S	N	M	M	M	5
36	Halliday and Resnick (1962)	N	S	N	S	M	M	6
37	Halliday, Resnick, and Walker (2008)	N	S	N	N	N	N	2
38	Halliday, Resnick, and Walker (1997)	N	S	N	N	N	N	2
39	Halliday, Resnick, and Walker (1993)	N	S	S	M	N	M	6
40	Hazen and Pidd (1965)	N	M	N	N	N	N	1
41	Hecht (2003)	N	S	E	M	S	S	10
42	Hecht (1998)	N	S	E	M	S	S	10
43	Hooper and Gwynne (1980)	N	S	N	N	N	N	2
44	Jones and Childers (1990)	N	S	N	N	N	N	2
45	Knight (2004)	M	S	N	M	N	N	4

Continued

TABLE 1 (Continued)

No.	Textbook	Criteria/Score[a,b] C1	C2	C3	C4	C5	C6	Total Score[c]
46	Lea and Burke (1997)	N	S	N	M	N	N	3
47	Lindsay and Margenau (1957)	N	N	N	N	N	N	0
48	Marion and Hornyak (1982)	N	S	N	S	N	N	4
49	Marshall and Pounder (1957)	N	N	N	N	N	N	0
50	McCormick (1965)	M	S	N	S	N	M	6
51	McGervey (1983)	M	M	N	S	N	N	4
52	Melissinos and Lobkowicz (1975)	N	S	N	N	N	N	2
53	Miller (1972)	N	M	N	N	N	N	1
54	Morgan (1964)	N	S	N	N	N	N	2
55	Nolan (1995)	N	N	N	N	N	N	0
56	Ohanian (1989)	N	S	N	S	N	N	4
57	Ohanian and Markert (2007)	N	S	N	S	N	N	4
58	Orear (1979)	N	S	M	N	N	N	3
59	Orear (1967)	N	S	N	N	N	N	2
60	Orear (1961)	N	M	N	N	N	N	1
61	Ostdiek and Bord (1991)	N	M	N	N	N	N	1
62	PSSC (1968)	N	M	N	N	N	N	1
63	Priestley (1958)	N	M	N	M	N	N	2
64	Radin and Folk (1982)	M	S	N	S	N	M	6
65	Reese (2000)	M	S	N	N	N	N	3
66	Richards et al. (1960)	N	S	N	N	N	N	2
67	Richtmyer, Kennard, and Lauritsen (1955)	M	M	N	M	N	M	4
68	Sears and Zemansky (1970)	N	N	M	N	N	N	1
69	Sears and Zemansky (1964)	N	M	M	N	N	N	2
70	Sears and Zemansky (1953)	N	M	N	N	N	N	1
71	Sears, Zemansky, and Young (1991)	N	M	N	N	N	N	1
72	Sears, Zemansky, and Young (1982)	N	M	N	N	N	N	1
73	Sears, Zemansky, and Young (1974)	N	M	M	N	N	N	2
74	Semat (1957)	N	N	N	N	N	N	0
75	Serway (1990)	N	S	N	N	N	N	2
76	Serway and Beichner (2000)	N	S	N	N	N	N	2
77	Serway and Jewett (2008)	N	S	N	N	N	N	2
78	Serway et al. (2006)	N	S	N	N	N	N	2
79	Serway and Faughn (1995)	M	S	N	N	N	N	3
80	Shortley and Williams (1971)	N	S	N	N	N	N	2
81	Shortley and Williams (1959)	N	S	N	N	N	N	2
82	Shortley and Williams (1950)	N	M	N	N	N	N	1
83	Tillery (1996)	N	M	N	N	N	N	1
84	Tilley (1976)	N	S	N	N	N	N	2
85	Tipler (1991)	M	S	N	S	N	N	5
86	Tipler (1987)	M	S	N	S	N	N	5
87	Tipler (1978)	M	S	N	S	N	N	5
88	Tippens (2007)	N	M	N	N	N	N	1
89	Touger (2006)	M	S	M	N	N	N	4
90	Urone (2001)	N	S	N	N	N	N	2
91	Van Name (1962)	N	S	N	S	N	N	4
92	Walker (2007)	N	S	M	N	N	N	3

Continued

TABLE 1 (Continued)

No.	Textbook	C1	C2	C3	C4	C5	C6	Total Score[c]
		Criteria/Score[a,b]						
93	Walker (2002)	N	S	M	N	N	N	3
94	Weidner and Browne (1985)	N	M	N	N	N	N	1
95	Weidner and Sells (1968)	N	M	N	N	N	N	1
96	White (1969)	N	M	N	S	N	N	3
97	Williams and Spangler (1981)	N	N	N	S	N	N	2
98	Wilson, Buffa, and Lou (2007)	N	N	N	N	N	N	0
99	Wolfson and Pasachoff (1995)	N	M	N	N	N	N	1
100	Young (1992)	M	S	N	M	N	N	4
101	Young and Freedman (1996)	M	S	N	M	N	N	4
102	Young and Gellar (2007)	M	S	N	M	N	N	4
103	Zafiratos (1976)	N	S	N	S	N	N	4

[a] C1: Lenard's trigger hypothesis to explain the photoelectric effect; C2: Einstein's quantum hypothesis to explain the photoelectric effect; C3: Lack of acceptance of Einstein's quantum hypothesis in the scientific community; C4: Millikan's experimental determination of the Einstein photoelectric equation and Planck's constant, *h*; C5: Millikan's presuppositions about the nature of light; C6: The historical record presented and its interpretation within a history and philosophy of science perspective.
[b] E = Excellent, S = Satisfactory, M = Mention; N = No mention.
[c] Textbooks were awarded the following points: E = 3, S = 2, M = 1, and N = 0.

spirit, he postulated that *every electromagnetic wave of frequency f is actually a stream of energy quanta, each with energy*:

$$\mathrm{E} = hf = \frac{hc}{\lambda}$$

. . . A photon colliding with an electron in a metal can vanish, imparting essentially all of its energy to the electron. (Emphasis in original, p. 1004)
. . .
A photon's energy goes into freeing the electron, and whatever is left appears as KE [kinetic energy]. When the electron is at the surface, the liberating energy is at a minimum, and the electron takes on a KE given by:

$$hf = \mathrm{KE}_{\max} + \phi$$

TABLE 2
Percentage of Textbooks with Each Score

Score	C1	C2	C3	C4	C5	C6	Average
	Criterion (%)						
No mention	84	14	84	69	95	91	73
Mention	16	39	11	16	2	7	15
Satisfactory	0	48	2	16	3	2	12
Excellent	0	0	3	0	0	0	0

> This wonderfully simple expression is known as **Einstein's Photoelectric Equation**, and it explains every aspect of the effect. Since $KE_{max} = hf - \phi$, increasing the intensity (i.e., irradiance) of the light leaves the maximum kinetic energy unchanged. Only by changing f is the KE_{max}, or equivalently, the stopping potential, changed for a given metal. (Emphasis in original, p. 1005)

Hecht's treatment is remarkable in that he explains the title of Einstein's article before presenting an explanation of Einstein's equation. Later in his presentation, Hecht also explains the straight line form of Einstein's equation, although he does not relate it to Einstein's explicit prediction of linearity.

Some textbooks explain the linear nature of Einstein's equation better than others. For example, Radin and Folk (1982) write

> The fact that $(KE)_{max}$ is predicted to be directly proportional to the frequency of light, f, as expressed in [the equation], has several consequences. First, $(K.E.)_{max}$ increases linearly with f. Second the slope of $(K.E.)_{max}$ vs. f is equal to Planck's constant, h, which had already been determined in connection with black-body radiation. (p. 766)

On the other hand, many textbooks refer to Einstein's quantum hypothesis but do not give enough essential detail to qualify as a "Mention." For example, Williams and Spangler (1981) write

> . . . Einstein proposed that a quantum model must be used to treat the ejection of electrons from a metal, its entire energy $E = hf$ is delivered to a *single* conduction electron within the metal, ... After acquiring the photon energy, the electron inside the metal has increased kinetic energy . . . . If eV_s represents the energy required for the most energetic electrons of the metal to move through the surface, then the Einstein photoelectric equation embodying these ideas is
>
> $$hf = (1/2)mv_{max}^2 + eV_s,$$
>
> where v_{max} is the maximum speed of electrons after the escape through the surface of the metal. (Italics in original, p. 891)

We note that this treatment only satisfies Criterion 2(c), namely, that light consists of localized quanta of energy, so that an electron in an atom will receive energy from only one photon at a time, and so it does not qualify for the minimum requirement of our criterion that specifies that a second aspect be included.

Criterion C3: Lack of Acceptance of Einstein's Quantum Hypothesis in the Scientific Community

Of the textbooks analyzed, 84% did not qualify at all in mentioning or discussing the lack of acceptance of Einstein's quantum hypothesis as proposed in his 1905 paper where he applied it to explaining the photoelectric effect. On the other hand, Criterion 3 also contained the only three evaluations of "Excellent" in the entire analysis. The scores of Excellent occurred for two editions of Hecht (1998 and 2003) and an earlier edition of Halliday and Resnick (1981). The best commentary occurs in Hecht:

> The idea of light-quanta was not received well at all, and it had very few early advocates. Paul Ehrenfest (who seems to have been independently thinking along similar lines in 1905), Max von Laue, and Johannes Stark (who in 1909 anticipated the Compton Effect, . . .) were the leading exceptions. Despite its clearly demonstrated theoretical power, it was so disconcerting to people educated in classical wave theory that it was especially slow to be accepted. When Planck recommended Einstein for membership in the Prussian Academy in 1913, he felt that, notwithstanding Einstein's demonstrated genius, he still had to apologize for him because "he may sometimes have missed the target in his speculations, as, for example, in his hypothesis of light-quanta." (p. 1028)

Although the authors developed the criteria before reading this passage in Hecht, it could not match the criteria more closely. Halliday and Resnick (1981) take a similar approach, writing that

> Although Millikan showed that this equation agreed with his experiment in every detail he himself remained unconvinced that Einstein's light particles were real. He wrote of Einstein's ". . . bold, not to say reckless, hypothesis . . . " and wrote further that Einstein's photon concept ". . . seems at present to be wholly untenable."
> Planck, the very originator of the constant, h, did not at once accept Einstein's photon's either. In recommending Einstein for membership in the Royal Prussian Academy of Sciences in 1913 he wrote: "that he may sometimes have missed the target in his speculations, as for example in his theory of light quanta, cannot really be held against him." Far from being unusual it is almost commonplace that truly novel ideas are accepted only slowly, even by such men of genius as Millikan and Planck. (p. 783)

By the time they write the above passage, Halliday and Resnick have also made it clear that Einstein's theory stood in opposition to the classical wave theory of light.

Most other textbooks do not fare nearly as well. Nolan (1995) states that "[i]n 1914, R. A. Millikan performed experiments . . . that confirmed Einstein's theory of the photoelectric effect" (p. 929). The counterhistorical notion portrayed here is that scientific theories can be proven true or false by empirical data. Prevalent in these presentations is the association of Millikan's experiment with Einstein's theory rather than with his equation.

Criterion C4: Millikan's Experimental Determination of the Einstein Photoelectric Equation and Planck's Constant, *h*

Of the 103 textbooks analyzed, 32 at least mention Millikan's experiment. Many of them portray Millikan as attempting to prove Einstein's *theory* as opposed to his *equation* and none of them point out that scientific theories are underdetermined by experimental evidence. The best description of Millikan's photoelectric experiment is given in Halliday and Resnick (1962):

> These data were taken by R. A. Millikan (1868–1953) whose painstaking work on the photoelectric effect won him the Nobel prize in 1923. Because the photoelectric effect is largely a surface phenomenon, it is necessary to avoid oxide films, grease, or other surface contaminants. Millikan devised a technique to cut shavings from the metal surface under vacuum conditions, a "machine shop *in vacuo*" as he called it. (p. 1089)

Halliday and Resnick, along with several other authors, use Millikan's original values in plotting the graph of stopping potential versus frequency. Only Lea and Burke (1997) reproduce Millikan's original graph and describe how Millikan determined the value of h from it.

Criterion C5: Millikan's Presuppositions About the Nature of Light

Of the six criteria formulated and applied to the textbooks, Criterion 5 fared the worst. Only five textbooks mention the presuppositions that dominated Millikan's beliefs when he set out to perform the photoelectric experiment. As has already been cited with Criterion 2, Halliday and Resnick (1981) point out that that Millikan showed that his experiment agreed exactly with Einstein's equation (as opposed to his theory). Hecht (1998) writes that "[n]ot until 1914–1915 would Robert Millikan finally and conclusively determine that the Photoelectric Equation was in complete agreement with experiment" (p. 1028). He also points out that the photoelectric effect "was so disconcerting to people educated in classical wave theory that it was especially slow to be accepted" (p. 1028).

In general, all of the textbooks are weak on pointing out that scientists have prior theoretical beliefs that they resist changing. In addition, the textbooks do not elaborate on the reasonableness of the belief in the wave theory of light around the time of the photoelectric effect.

Criterion C6: The Historical Record Presented and Its Interpretation Within a History and Philosophy of Science Perspective

The analysis reveals that very few textbooks have the section on the photoelectric effect written from an overall HPS perspective. The two Hecht editions (1998 and 2003) come closest to the requirements. These editions include significant and accurate historical details that are accurately portrayed from the HPS perspective. The only component lacking is an account of Lenard's trigger hypothesis to explain the photoelectric effect.

Other textbooks contain a few HPS aspects. For example, McCormick (1965) writes about classical wave theory that "[a]ccording to classical wave theory, the velocity of a photoelectron should depend upon the amplitude of the electric field vector in the incident waves and, therefore, upon the intensity rather than the frequency" (p. 713). Richtmyer, Kennard, and Lauritsen (1955) describe Lenard's work and refer to the trigger hypothesis, although not linking it directly to Lenard. They write about Einstein's equation:

> It was first proposed on theoretical grounds by Einstein, in 1905, as a result of the extension to the photoelectric process of the concept, previously developed by Planck, that interchanges of energy between radiation and matter take place in energy quanta of magnitude $h\nu$, where ν is the frequency of the radiation absorbed or emitted and h is a constant. Einstein assumed that the whole quantum $h\nu$ of radiant energy was absorbed by one electron but that a part ω_0 of it was expended by the electron escaping from the matter. Only qualitative data were available at that time showing that his equation gave results of the right order of magnitude, but subsequently the equation received final experimental verification as a result of the precise experiments of Millikan. . . . But in spite of its generality and of the many successful applications that have been made of it in physical theories, the equation is, as we shall see presently, based on a concept of radiation—the concept of "light quanta"—completely at variance with the most fundamental concepts of the classical electromagnetic theory of radiation. (p. 94)

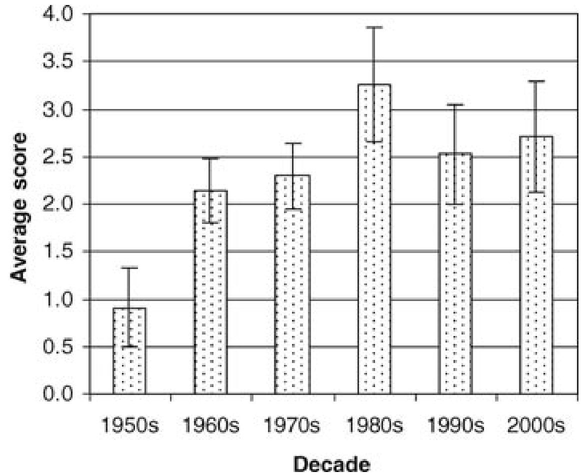

Figure 1. Plot of the time distribution of textbook scores.

Unfortunately, Richtmyer et al. do not include other essential elements, such as describing Millikan's experiment or showing his graph. Moreover, they do not point out that Einstein predicted the linear dependence of stopping potential on light frequency, which would allow the determination of h.

A Temporal Analysis of Textbook Scores

The 103 textbooks that served as the sample in our analysis have a fairly even distribution in their publication dates beginning in 1950 and continuing to the present. After the initial analysis, which provided a total score for each textbook, it became possible to analyze the score as a function of publication date. For this purpose the publication dates were divided into decades. The results are presented in Table 3 and plotted in Figure 1. It is apparent that textbooks scored significantly better beginning in the 1960s as compared to the 1950s. We speculate that the trend may be a byproduct of the massive science education reform begun in the United States after the Sputnik launch in 1957, which resulted in the passing of the National Defense Education Act the following year. Around that time, the term "scientific literacy" was first used (Hurd, 1958), and T. S. Kuhn's influential *Structure of Scientific Revolutions* (1962/1996) was published. More high-quality secondary history of science materials became available. The first history of science-based physics textbook, *Project*

TABLE 3
Time Distribution of Textbook Scores by Decade

Decade	Average Score	Standard Error	*n*
1950s	0.9	0.4	11
1960s	2.1	0.3	21
1970s	2.3	0.3	17
1980s	3.3	0.6	16
1990s	2.5	0.5	21
2000s	2.7	0.6	17

Physics (Rutherford, Holton, & Watson, 1970), was published soon thereafter. The graph also shows that the massive educational reform efforts begun in the 1990s (cf. Rutherford & Algren, 1990; AAAS, 1993) appear not to have had any appreciable effect on general physics textbooks as far as the HPS approach is concerned.

CONCLUSION AND EDUCATIONAL IMPLICATIONS

The lack of inclusion of a coherent history of science context or a clear history and philosophy of science perspective in the textbooks is disappointing although not altogether surprising. The fundamental lack of context in textbooks is well established (Klassen, 2006). Ironically, textbooks are an essential component of school and tertiary-level science, which is at fundamental odds with scientists' science or "science-in-the-making" (Klassen, 2006; Niaz, 2008). Formal science learning operates by the dominant methodology of *normal science education* (Van Berkel et al., 2000), which is characterized by oversimplification and dependency on textbooks (T. Kuhn, 1963) and tends to lack context, imagination, and engagement. Science has come to be represented both in scientists' science and school and tertiary-level science as a form of decontextualized and dehumanized "history" (Klassen, 2006). An effective way in which to bridge the gap between school science and what scientists actually do is through the inclusion of an accurate history of science, which has been especially crafted for science students (Stinner, McMillan, Metz, Jilek, & Klassen, 2003). History of science can be used to bring scientific concepts to science learning in a way that humanizes the protagonists and provides an appropriate context (Klassen, 2006). On the basis of various episodes from the history of science (including the photoelectric effect), Niaz (2009) has shown that interpretation of experiments is difficult and inevitably leads to alternative models/theories, thus facilitating the understanding of science as a dynamic human enterprise.

We recommend that historical presentations like our reconstruction should be an integral part of the presentation of the photoelectric effect in textbooks. In other words, historical details do not have to be presented in special sections or sidebars of the textbooks. For example, mention of Lenard's contribution (trigger hypothesis) before Einstein's hypothesis of lightquanta, difficulties associated with Einstein's hypothesis, Millikan's experimental determination of the photoelectric equation, and Millikan's rejection of Einstein's hypothesis based on his presuppositions, clearly constitute important elements of an unfolding story (Stinner et al., 2003). Bevilacqua and Bordoni (1998) have also endorsed such a historical approach: "We are not interested in adding the history of physics to teaching physics, as an optional subject: the history of physics is 'inside' physics" (p. 451).

It is plausible to suggest that the inclusion in textbooks of the following aspects related to the photoelectric effect can facilitate a better understanding of the dynamics of scientific progress: (a) Einstein's quantum hypothesis constituted a rival to Lenard's trigger hypothesis; (b) Einstein's hypothesis was not accepted by the scientific community, including Planck, the "originator" of the quantum hypothesis, for many years; (c) Millikan presented experimental evidence to support Einstein's photoelectric equation and still rejected his quantum hypothesis; (d) scientific theories are underdetermined by experimental evidence, that is, no amount of experimental evidence can provide conclusive proof for a theory (these aspects can be included in the textbooks by presenting Millikan's experimental determination and at the same time pointing out that this was not considered as sufficient evidence for Einstein's theory); (e) scientists customarily have prior theoretical beliefs or presuppositions before doing an experiment, and they resist any change in those epistemological beliefs; and (f) an overview of the historical reconstruction as provided in

Criterion 6 (Lenard, Einstein and opposition, Millikan's experiments and presuppositions), which can help teachers and textbook authors to coordinate the different objectives. For further details, we suggest that the reader may consult Klassen (2009b) who has developed a classroom teaching strategy to introduce the historical aspects of the photoelectric effect as an unfolding story.

Finally, it is important to note that general physics textbooks not only lack a HPS perspective but also ignore various NOS aspects, such as (a) the theory-laden nature of observations (both Millikan and Einstein interpreted the data based on their theoretical frameworks), (b) the tentative nature of scientific knowledge (explanations for the photoelectric effect changed over the years), (c) rival hypotheses to explain the same experimental data (Lenard's trigger hypothesis and Einstein's light quanta), and (d) the underdetermination of scientific theories by experimental evidence.

APPENDIX A: LIST OF INTRODUCTORY PHYSICS TEXTBOOKS ANALYZED IN THIS STUDY ($n = 103$)

Acosta, V., Cowan, C. L., & Graham, B. J. (1973). Essentials of modern physics (1st ed.). New York: Harper & Row.

Arfken, G. B., Griffing, D. F., Kelly, D. C., & Priest, J. (1989). University physics volume II (2nd ed.). San Diego, CA: Harcourt Brace Jovanovich.

Atkins, K. R. (1965). Physics (1st ed.). New York: Wiley.

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Beiser, A. (1979). Modern technical physics (3rd ed.). Menlo Park, CA: Benjamin/Cummings.

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Blackwood, O., & Kelly, W. (1955). General physics (2nd ed.). New York: Wiley.

Blanchard, C. H., Burnett, C. R., Stoner, R. G., & Weber, R. L. (1958). Introduction to modern physics (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.

Borowitz, S., & Bornstein, L. A. (1968). A contemporary view of elementary physics (1st ed.). New York: McGraw-Hill.

Bueche, F. (1965). Principles of physics (1st ed.). New York: McGraw-Hill.

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Bueche, F. J. (1975). Introduction to physics for scientists and engineers (2nd ed.). New York: McGraw-Hill.

Bueche, F. J. (1980). Introduction to physics for scientists and engineers (3rd ed.). New York: McGraw-Hill.

Bueche, F. J. (1986). Introduction to physics for scientists and engineers (4th ed.). New York: McGraw-Hill.

Bueche, F., & Wallach, D. L. (1994). Technical physics (4th ed.). New York: Wiley.

Coletta, V. P. (1995). College physics (1st ed.). St. Louis, MO: Mosby.

Cooper, L. N. (1968). An introduction to the meaning and structure of physics (1st ed.). New York: HarperCollins.

Cooper, L. N. (1992). Physics: Structure and meaning (1st ed.). Hanover, NH: University Press of New England.

Copeland, P. L., & Bennett, W. E. (1961). Elements of modern physics (1st ed.). New York: Oxford University Press.

Cutnell, J. D., & Johnson, K. W. (2007). Physics (7th ed.). Hoboken, NJ: Wiley.
Dull, C. E., Metcalfe, H. H., & Williams, J. E. (1964). Modern physics (1st ed.). New York: Holt, Rinehart and Winston.
Durbin, F. M. (1955). Introduction to physics (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
Eisberg, R. M., & Lerner, L. S. (1981). Physics foundations and applications combined volume (1st ed.). New York: McGraw-Hill.
Fishbane, P. M., Gasiorowicz, S. G., & Thornton, S. T. (1993). Physics for scientists and engineers (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
Fishbane, P. M., Gasiorowicz, S. G., & Thornton, S. T. (2005). Physics for scientists and engineers with modern physics (3rd ed.). Upper Saddle River, NJ: Pearson Prentice-Hall.
Gamow, G., & Cleveland, J. M. (1960). Physics: Foundations and frontiers (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
Gettys, W. E., Keller, F. J., & Skove, M. J. (1989). Physics classical and modern (1st ed.). New York: McGraw-Hill.
Giancoli, D. C. (1984). General physics (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
Giancoli, D. C. (1998). Physics principles with applications (5th ed.). Upper Saddle River, NJ: Prentice-Hall.
Greenberg, L. H. (1978). Physics with modern applications (1st ed.). Philadelphia: Saunders.
Greene, E. S. (1962). Principles of physics (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
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Halliday, D., Resnick, R., & Walker, J. (2008). Fundamentals of physics (8th ed.). New York: Wiley.
Hazen, W. E., & Pidd, R. W. (1965). Physics (1st ed.). Reading, MA: Addison-Wesley.
Hecht, E. (1998). Physics: Algebra/trig (2nd ed.). Pacific Grove, CA: Brooks/Cole.
Hecht, E. (2003). Physics: Algebra/trig (3rd ed.). Pacific Grove, CA: Thomson Brooks/Cole.
Hooper, H. O., & Gwynne, P. (1980). Physics and the physical perspective (2nd ed.). San Francisco: Harper & Row.
Jones, E. R., & Childers, R. L. (1990). Contemporary college physics (1st ed.). Reading, MA: Addison-Wesley.
Knight, R. D. (2004). Physics for scientists and engineers: A strategic approach (1st ed.). San Francisco: Pearson Addison-Wesley.
Lea, S. M., & Burke, J. R. (1997). Physics: The nature of things (1st ed.). Pacific Grove, CA: Brooks/Cole.

Lindsay, R. B., & Margenau, H. (1957). Foundations of physics (1st ed.). New York: Dover.
Marion, J. B., & Hornyak, W. F. (1982). Physics for science and engineering, Part 2 (1st ed.). Philadelphia: Saunders College.
Marshall, J. S., & Pounder, E. R. (1957). Physics (1st ed.). Toronto, Ontario, Canada: Macmillan.
McCormick, W. W. (1965). Fundamentals of college physics (1st ed.). New York: Macmillan.
McGervey, J. D. (1983). Introduction to modern physics (2nd ed.). New York: Academic Press.
Melissinos, A. C., & Lobkowicz, F. (1975). Physics for scientists and engineers, volume II (1st ed.). Philadelphia: W.B. Saunders.
Miller, F. (1972). College physics (3rd ed.). New York: Harcourt Brace Jovanovich.
Morgan, J. (1964). Introduction to university physics, volume II (1st ed.). Boston: Allyn and Bacon.
Nolan, P. J. (1995). Fundamentals of college physics volume 2 (2nd ed.). Dubuque, IA: Wm. C. Brown.
Ohanian, H. C. (1989). Physics (2nd ed.). New York: Norton.
Ohanian, H. C., & Markert, J. T. (2007). Physics for scientists and engineers volume III (3rd ed.). New York: W.W. Norton.
Orear, J. (1961). Fundamental physics (1st ed.). New York: Wiley.
Orear, J. (1967). Fundamental physics (2nd ed.). New York: Wiley.
Orear, J. (1979). Physics (1st ed.). New York: Macmillan.
Ostdiek, V. J., & Bord, D. J. (1991). Inquiry into physics (2nd ed.). St Paul, MN: West Publishing.
Physical Science Study Committee. (1968). College physics (1st ed.). Boston, MA: Raytheon.
Priestley, H. (1958). Introductory physics a historical approach (1st ed.). Boston: Allyn and Bacon.
Radin, S. H., & Folk, R. T. (1982). Physics for scientists and engineers (1st ed.). Englewood Cliffs, NJ: Prentice-Hall.
Reese, R. L. (2000). University physics (1st ed.). Pacific Grove, CA: Brooks/Cole.
Richards, J. A., Sears, F. W., Wehr, M. R., & Zemansky, M. W. (1960). Modern university physics (1st ed.). Reading, MA: Addison-Wesley.
Richtmyer, F. K., Kennard, E. H., & Lauritsen, T. (1955). Introduction to modern physics (5th ed.). New York: McGraw-Hill.
Sears, F. W., & Zemansky, M. W. (1953). College physics (2nd ed.). Cambridge, MA: Addison-Wesley.
Sears, F. W., & Zemansky, M. W. (1964). University physics (3rd ed.). Reading, MA: Addison-Wesley.
Sears, F. W., & Zemansky, M. W. (1970). University physics (4th ed.). Reading, MA: Addison-Wesley.
Sears, F. W., Zemansky, M. W., & Young, H. D. (1974). College physics (4th ed.). Reading, MA: Addison-Wesley.
Sears, F. W., Zemansky, M. W., & Young, H. D. (1982). University physics (6th ed.). Reading, MA: Addison-Wesley.
Sears, F. W., Zemansky, M. W., & Young, H. D. (1991). College physics (7th ed.). Reading, MA: Addison-Wesley.
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Van Name, F. W. (1962). Modern physics (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.
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Zafiratos, C. (1976). Physics (1st ed.). New York: Wiley.

APPENDIX B: VALIDATION OF CRITERIA FOR EVALUATION OF TEXTBOOKS

	Percentage of Intercoder Agreement on Six Criteria					
Stage	1	2	3	4	5	6
1						
Textbook 1	50	75	75	75	100	100
2						
Textbook 2	75	75	75	100	75	100
Textbook 3	75	75	100	100	100	100
3						
Textbook 4	100	100	75	100	100	100
4						
Textbook 5	100	75	100	100	100	100
Textbook 6	100	100	100	100	100	100
5						
Textbook 7	100	75	100	100	100	100
Textbook 8	100	75	100	100	100	100
Textbook 9	100	100	100	100	100	100

Note: Stages represent the days on which the four coders met to compare their evaluations. Stage 1: day 1, Stage 2: day 3, Stage 3: day 8, Stage 4: day 9, Stage 5: day 11. Thus, the validation process lasted 11 days, which provided sufficient time for revision and exchange of ideas with respect to the six criteria. Each meeting lasted about 2 hours.

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