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A Sense of History: History of Science and the Teaching of Introductory Quantum Theory

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ABSTRACT: This paper argues that some kind of historical perspective is a *conditio sine qua non* in the teaching of physics. Without a proper historical perspective the student will not experience physics as the living, human endeavour it is; in addition, the historical-exemplaric approach is often beneficial also to the technical and conceptual aspects of physics education by offering a deeper and more critical look at particular physical problems. However, the relationship between physics and history of physics is intrinsically problematic in that the lessons to be learned from history are often counterproductive to those aimed at in science teaching. The tensions between the two approaches may lead to a historically unsatisfactory quasi-history adapted to the perceived needs of science education, but although this dilemma is genuine, there is no reason why it should block a historically oriented teaching of physics. Based on the example of the history of the photoelectric effect as a case in the teaching of introductory quantum theory it is argued that the dilemma between 'historical truth' and 'didactic usefulness' may be circumvented by focussing on a few, carefully selected case studies. The didactic potentials of one such example, the early introduction of the light-quantum, are discussed.

1. INTRODUCTION

Besides a couple of less acceptable reasons, to be mentioned below, there are two good reasons for introducing a historical perspective in the teaching of science. First of all, science is an integral part of culture and has, as all cultural manifestations, underwent big changes throughout history. Although not the result of a simple cumulative process, present scientific knowledge is nonetheless the outcome of a dynamic-historical process which still goes on and is part of the very soul of science. Without the recognition of this historical nature, the development and impact of science cannot be understood. Students (and all other people) should know at least the rudiments of man's changing conceptions of nature; they should know about the Copernican world-view and the impact of Darwinism for the same ideal reasons that they should know about Greek architecture, romantic literature and the emergence of capitalist economy.

The second reason for a historically oriented science teaching relates to the sciences themselves and their role in modern society. In order to understand what science 'is' and how scientific knowledge progresses, history of science is indispensable. We may distinguish between two components of this methodological use of history. The broad perspective, say the development of astronomy from Ptolemy to Hubble, is necessary for an understanding of the transitory aspects of science; it brings home the essential insight that science is a dynamic phenomenon and that current knowledge is likely to change drastically in the future. This broad perspective does not require specialized knowledge and does not necessarily belong to the science curriculum. Indeed, it has, if taught at all, traditionally been part of the history curriculum, which perhaps is its proper place. But a more accurate understanding of scientific reasoning, as it takes place in the real world, requires more specialized knowledge and hence must be the responsibility of the science teachers. For practical reasons it is not possible (nor, I think, desirable) to teach a scientific subject in a thoroughly historic perspective; but it is quite possible, and highly profitable, to focus on select case-studies. That is, to use historical events exemplarically.

Whatever approach is adopted, an important part of science teaching in a historical perspective is to question the 'standard view' of science which most students presumably hold, and which is propagated through textbooks, tradition and mass media. This is the view that science is a-historical; that scientific knowledge progresses by a definite 'scientific method' which renders it absolute and beyond criticism; that scientific discussions are always detached and objective; and that science is an indisputable benefit for society. Simply by sticking closer to the historical events, including events of the most recent history, this picture will fade. Almost all cases from the history of science demonstrate the difficulty in obtaining consensus, the controversies, the interaction with external forces, and the metaphysical foundations on which many scientific arguments rest. Dissemination of such insight is important in an age where science is cultivated as a substitution for religion. But of course it is problematic because of the danger of throwing the baby out with the bathwater: Science is not a divine expert activity, but neither is it a fashion we can handle as we find best. We would like students to be critical and knowledgeable, not to think of science in relativistic terms or to adopt an anything-goes quasi-methodology. At least I would not. History of science can be used in many ways, to substantiate the 'standard view', to argue the cause of radical relativism, or to demonstrate the dynamic and intricate nature of scientific reasoning. It all depends on the way in which history is practised in concrete teaching situations.

It is important to point out that not any kind of historical perspective is beneficial or acceptable. One kind of motivation for introducing a measure of history in science education is the wish to present especially the hard sciences in softened versions, as humanistic endeavours; and thereby making them more popular among students who might otherwise be scared by these subjects. Or, what is more common, to flavour the exposition with historical anecdotes and stray biographical data here and there. This may be done with more or less respect for historical facts, but it generally tends to reduce the historical dimension of science to the chronological and anecdotal level; something which may be amusing, but has no authority compared to the 'real content' of the textbook. And the humanizing endeavour tends to present the sciences as merely humanistic disciplines, which they are not. Students exposed to such propaganda in school may in this way overcome their fear for physics, or what they believe is physics. But at some stage they will discover, to their grim surprise, that there is a big difference between studying physics and reading a historical novel about physics.

There are many more problems in introducing history of science in science teaching which I must refrain from mentioning. The principal point I want to make in this paper is that use of exemplary cases offer an opportunity to discuss historical material in a relatively comprehensive and authentic way. The lessons to be learned from such case-studies will usually diverge from those originating from the textbook versions of history of science, but all the better for that. The kind of history presented explicitly or implicitly in science textbooks belongs to what has been called quasi-history, that is, a mythical history specially prepared for the indoctrination of certain methodological and didactic viewpoints. I shall return to this question in Section 7, where I argue that there are educational advantages as well as problems in replacing quasi-history with history.

2. THE JUSTIFICATION OF THE QUANTUM POSTULATE

Virtually all textbooks introduce the quantum postulate – that is, the necessity of conceiving physical processes as discontinuous at the atomic or subatomic level – by referring to a number of experimental facts which were discovered in the early part of the twentieth century and which seem inexplicable without the hypothesis of quantization. The phenomena discussed are usually blackbody radiation, photoelectric effect, X-ray and optical line spectra, and Compton scattering. The didactic point in this presentation is not that the students should know about the history of these experimental foundations because of their historical importance; they are merely used as means for persuading students that energy quantization is an inescapable conclusion. Reasonably enough, emphasis is placed on physics, and not on history of physics. Yet, these introductions are framed historically, giving the impression that they are reliable summary accounts of the actual development of the thoughts that led to the acceptance of quantum theory. The idea is clearly to reconstruct bits of the past and in this way convince the students that the conclusion drawn by physicists of the past was the only rational one, and the one which also modern students of physics have to accept. Since it is rational to accept unequivocal experimental results, the history of early quantum theory is presented as a cumulative sequence of experiments which all point to energy quantization. In other words, not only is it rational to accept the quantum postulate, this idea was also introduced historically in a rational way, which then serves a didactic purpose. The problem is that the didactic aim is often contradicted by the actual course of history, which makes it tempting to invent a quasi-history for educational purposes.

The photoelectric effect is the liberation of electrons from the surface of a metal illuminated by light. The energy of the photoelectrons can be measured by applying a counter-voltage which stops the photocurrent. The phenomenon, because it is easily understandable and reproducable in school laboratories, inevitably plays an important part in text-books' introduction of the quantization of light energy.[1] With few exceptions, the structure in these accounts is the following. About 1900 the understanding of photoelectricity was in a state of crisis because its details could not be explained by classical optical theory. Then, in 1905, Einstein brilliantly resolved the crisis by applying Planck's hypothesis of energy quantization to light, which led him to conceive light as a stream of energy quanta, later called photons. Since Einstein's theory accorded with experiments, and classical theory did not, it was quickly adopted by the physicists.

Of course textbooks differ in their treatments of the photoelectric effect, but a cursory survey of the literature shows that most of the elements in the mentioned version are repeated in the majority of textbooks. One example, taken from a teacher's guide, is the following:[2]

> In 1905 Einstein used the quantum theory with great success to explain the photoelectric effect. . . . [On classical wave theory] we should expect that radiation of sufficient amplitude would provide sufficient energy to dislodge the electrons and that the effect would be independent of the frequency. . . . [Einstein's explanation] was valuable evidence in support of Planck's idea, and since radiation had been shown to be both emitted and absorbed as quanta it was reasonable to suppose that energy existed as quanta all the time.

Needless to say, this version of the history of the photoelectric effect is grossly oversimplified and contains several myths or plain errors. Among the myths which usually enter the quasi-historical presentation, are the following: (1) Einstein's theory of 1905 relied upon and was a natural extension of Planck's theory of 1900, which Einstein adopted and applied to the nature of light; (2) Einstein's work was a theory of the photoelectric effect; (3) The core of Einstein's theory was an explanation of experiments which proved that the kinetic energy of the photoelectrons depends linearly on the frequency of light, but is independent of its intensity; (4) This experimental fact was (and is) inexplicable without the photon hypothesis; (5) Since there thus was no classical alternative to Einstein's explanation, it was of course accepted; (6) The final verification of Einstein's theory was provided by Millikan in experiments of 1916.

As I shall argue, all these assertions are misrepresentations of the actual history.[3] But they are essential for using the history of the photoelectric effect in the way textbooks do. Without them, the history would not function as a means of educating students in what is considered the proper methods of science.

3. PHOTOELECTRIC EFFECT WITHOUT THE PHOTON

A simple and pedagogically satisfying way of explaining changes in scientific theory is to ascribe them to anomalies, that is, to experimental facts that contradict existing theory and then provoke a new theory in response to an empirical problem. It is this empiricist or 'experimenticist' approach which lies behind the claim, often found in textbooks, that special relativity originated as a response to the Michelson-Morley ether drift experiments.[4] Applying the same kind of justification it is sometimes claimed that 'In 1905 Albert Einstein proposed an explanation for the dependence of photoelectric emission on the frequency of the radiation'.[5] But Einstein's theory was not aimed at explaining an anomaly within the classical framework, the linear dependence of electron energy on the frequency of incident light. For no such anomaly existed. In Philipp Lenard's Nobel prize rewarded experiments of 1902, the German physicist proved that the photocurrent is proportional to the intensity of light, but independent of its wavelength. He also found that the maximum kinetic energy of the emitted electrons (E_m) does not vary with the intensity, but Lenard did not investigate the exact relationship between E_m and the frequency (ν). This, incidentally, is a nice illustration of how theoretical expectations govern experiments: Lenard had no reason to expect a (E_m, ν) relationship, and so he ignored it. The point is that by 1905, when Einstein took up the matter, there did not exist any experimental data which suggested a linear relationship between energy and frequency. The famous equation $E_m = h\nu - P$ simply did not exist, not even as an empirical rule. By that reason alone, Einstein's theory could not possibly be a theoretical response to an experimental anomaly.

But didn't Lenard's observation of the independence of E_m on the frequency of light constitute a problem in need of explanation, an anomaly? After all, according to classical theory the intensity is a measure of the energy of light, and then energy conservation seems to require an electron energy increasing with intensity. Textbooks often makes a point out of this and emphasize that classical theory is wholly unable to explain that all the energy in a high-intensity, but low-frequency beam of light cannot liberate one single electron. How puzzling, and how devastating to the classical conception of light![6] Unfortunately, the argument is flawed both logically and historically. As to logic, the observation only leads to inconsistency with classical theory if it is assumed that the mechanism involved is a transmission of energy from the light to the electrons. Such an assumption may be natural, but it is certainly not compelling and was not, in fact, made by most physicists about 1905. In 1902 Lenard thus argued that there was indeed an inconsistency, but one between (a) the classical notion of light, (b) experiments, and (c) the hypothesis that photoelectric effect is an energy transmitting process. If any of these premises are discarded, the problem would vanish. Lenard concluded that premise (c) had to be wrong, and that the photoelectric effect therefore had to be explained by a different kind of mechanism. Logically, he might just as well have doubted the validity of (a), or even (b), or any combination of the three, but this would only lead to more problems. By choosing to criticize the weakest of the assumptions, Lenard acted rationally.

As an alternative to assumption (c) Lenard proposed what has been called the trigger hypothesis, namely that the energy distribution of the photoelectrons is not determined by the light, but by the internal structure of the atoms of the photo cathode. As a crude model of the atom he assumed that it consisted of a large number of electrons, each with a characteristic velocity and corresponding characteristic frequency; an incident ray of monochromatic light would then, he figured, release or 'trigger' the electron whose frequency was in resonance with the frequency of the light. Since one of the atomic electrons would have a maximum velocity, the E_m of the photoelectrons would depend on the cathode metal and the spectral composition of the light, in agreement with observations. With this kind of model, Lenard could explain the photoelectric effect without involving energy exchange and without questioning the classical theory of light. Although it was only a rough sketch of explanation, it was neither speculative nor clearly ad hoc. It was not put forward in order to save the wave theory of light (which was taken for granted) and it had a certain support in and affinity to current views of the structure of the atom. The trigger hypothesis was, at any rate, widely accepted among physicists, who consequently did not consider the photoelectric effect incompatible with the classical theory of light. Rudolf Ladenburg's opinion of 1909, that Lenard's hypothesis belonged to 'the generally accepted truths of physics' was for a time widely shared.[7]

4. EINSTEIN'S THEORY

In 1905 Einstein proposed that light consists of, or may fruitfully be conceived as consisting of, light quanta.[8] In his careful theoretical argumentation, the photoelectric effect was only one component, and not the central one. Since only 3 pages out of the article's 17 pages deal with the photoelectric effect, it is misplaced to refer to the paper as 'a theory of the photoelectric effect'. The basis of Einstein's argumentation was the laws of blackbody radiation, but it was in no way a continuation of Planck's law of 1900, and the famous Planck constant (h) did not even enter as an independent variable in Einstein's work. He did not take his departure in Planck's 'revolutionary' radiation law – retrospectively celebrated as the birth of quantum theory – but in Wilhelm Wien's nonquantum law of 1896, which is valid only for high frequencies. The reason was that Einstein in 1905 believed that Planck's theory could not be made to agree with the idea of light quanta.[9] The hypothesis of light quanta of energy $E = h\nu$ was introduced theoretically and not as a response to photoelectric experiments. These experiments played a role, but mainly as additional justification of an already introduced idea. By conceiving the photoelectric effect as an energy exchange process, Einstein then deduced the famous equation $E_m = h\nu - P$, where P is the work function of the cathode metal. Since there was no experimental evidence for such a relationship in 1905, Einstein's deduction was a *prediction*.

Einstein's account of the photoelectric effect included a mechanism for its production as well as a genuine prediction of an experimentally testable relationship; it also agreed with Lenard's observations, was simple, and founded on a general theory of light with several testable consequences. It is therefore easy to understand that his theory of the photoelectric effect was readily accepted and acted as a decisive argument for the wider theory of light quanta and energy quantization. This, at least, is what students are been told in textbooks. Even some scholarly works, such as Max Jammer's still authoritative *Conceptual Foundation of Quantum Mechanics*, add support to this interpretation. 'Owing to Einstein's paper of 1905', Jammer writes, 'it was primarily the photoelectric effect to which physicists referred as an irrefutable demonstration of the existence of photons'.[10]

The textbook version is wrong. In fact the photoelectric effect played only a peripheral role during the gradual acceptance of the quantum theory between 1900 and 1915, and Einstein's celebrated theory was simply not considered a serious alternative in the physics community. The reason was not that Einstein was a genius (although he was) and the other physicists conservatives clinging to an old world view (although some were). Physicists, including Einstein, realized that there was a high price to pay for the acceptance of the theory, namely the abandonment of the entire electromagnetic wave theory of light, one of the most impressive and best confirmed theories of physics. Most physicists were unwilling to pay the price and unimpressed by Einstein's (E_m, ν) prediction. After all, this prediction had no experimental support, and even if it would be verified it would not count as a crucial experiment: although a linear dependency of E_m on ν did not follow from Lenard's trigger hypothesis, neither did it contradict it. The radicality of Einstein's theory in its being incompatible with the well-established wave theory of light caused most physicists either to ignore it or to criticize it as speculative and ill-founded. Planck's often-cited evaluation, when he, together with Nernst, Rubens and Warburg, proposed Einstein for membership of the Prussian Academy in 1913 exemplifies the general attitude: 'That he [Einstein] may sometimes have missed the target in his speculations, as, for example, in his hypothesis of light-quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk'.[11]

5. THEORY VERSUS EQUATION

From about 1907 several experimental physicists became interested in determining what kind of relationship there existed between the energy of the photoelectrons and the frequency of the incident light. Eventually, Einstein's prediction became brilliantly confirmed, which retrospectively was seen as a confirmation also of Einstein's theory of light quanta and an exemplaric case of fruitful cooperation between theory and experiment. This rationalization of the events lives on in textbooks and physicists' working history of their field. It has little to with with the historical realities.

The first systematic experiments to find a (E_m, ν) relationship were not conducted in order to test Einstein's equation, but took place within the framework of Lenard's theory. This theory, based on the trigger hypothesis, gradually became discredited and had disappeared about 1912. The reason was not that Einstein's alternative superseded it, which it only did much later; and neither was it refuted directly, for Lenard's qualitative and vague theory was not easily refutable. The trigger hypothesis was abandoned because experiments indicated that the idea of light activating matter without energy exchange was not tenable. Ironically, but to Lenard's credit, this insight was primarily based on experiments on photoinduced gas ionization which he and Carl Ramsauer conducted in 1911. They showed that the ionization was always followed by an absorption of light energy, which evidently contradicted the idea of nonenergetic interaction.

However, the abandonment of Lenard's hypothesis did not imply an acceptance of Einstein's theory. There were several non-Einsteinian ways of explaining the photoelectric effects, and for a time these were seen as more promising than Einstein's radical alternative. The advocates of such classical or semi-classical theories included prominent physicists such as J. J. Thomson, Arnold Sommerfeld, H. A. Lorentz, Pieter Debye and Max Planck. I shall not try to outline the content of these theories, but only mention that they all conceived photoelectric effect as a kind of resonance phenomenon where the eigen-motions of the atomic electrons were released by an incoming light wave. The kinetic energy of the electrons were not transferred from the light, but pre-existed within the atoms. To this extent, and to the extent that these theories focused on the atomic structure as the key for understanding photoelectricity, they were in the Lenard tradition. Both Sommerfeld, Planck and Thomson managed to produce classical (i.e., non-photon) theories of the photoelectric effect which included a linear relationship between E_m and ν. And so did Owen Richardson, who in 1912 proposed another theory of the photoelectric effect which avoided microphysical assumptions at all. Richardson deduced from his theory exactly the same equation as Einstein had obtained in 1905.

As these non-Einsteinian interpretations show, it was quite possible to derive Einstein's *equation* without using Einstein's *theory*. In general it is important to distinguish theories from equations, by other reasons because it is usually the equation which is tested empirically, and not the theory. If the same equation can be arrived at from different theories, what does agreement with measurement imply? Not, apparently, that any particular of the theories is verified. This situation is general in the testing of theories, and part of the reason why experiments often fail to produce unambiguous evidence for or against a particular theory.

For example, when experimental evidence indicated a linear relationship about 1912, Richardson noted with satisfaction that a confirmation of Einstein's equation did not mean a confirmation of 'the restricted and doubtful hypothesis used by Einstein'.[12] It might just as well be taken as support of alternative theories, such as his own. By various reasons, especially the acceptance of Bohr's quantum model of the atom, the non-Einsteinian theories were abandoned about 1914, which left Einstein's theory alone in offering an explanation of the photoelectric effect. In such a situation the only rational thing to do, it seems, would be to accept Einstein's theory; for, as philosophers of science have argued, a controversial theory is better than no theory. But whatever the view of philosophers, this was not what happened. During the period from about 1914 to 1922 physicists were quite willing to be without a theoretical explanation of photoelectricity. The favoured strategy was to accept Einstein's equation, but to consider it a phenomenological law and not a consequence of Einstein's theory of light quanta.

6. TESTING

The experimental determination of the (E_m, ν) relationship is nowadays performed in student courses with ready-made apparatus. The entire experiment lasts some 20 minutes. Historically it took about 10 years, from 1906 to 1916, to reach the conclusion that energy and frequency are indeed related as Einstein predicted. Moreover, for several years the experimental data showed a confusing disparity which could not even be taken as support of Einstein's equation. One of the first experimenters to investigate the matter, Erich Ladenburg, concluded that E_m varied as the square of the frequency, while Abraham Joffé's analysis *of the same data* led him to conclude a linear relationship. To make the confusion complete, Frederick A. Lindemann argued in 1911 that $E_m \sim \nu^{2/3}$. New and more precise measurements performed in the USA in 1912–14 by Arthur L. Hughes, by W. H. Kadesch, and by Richardson and Karl Compton, indicated linearity. Their conclusion was criticized by other researchers, including Robert Pohl and Peter Pringsheim in Germany who believed that the best fit resulted in a logarithmic relationship ($E_m \sim ln\ \nu$). Without supporting any of the alternatives, Ramsauer concluded in a comprehensive review of 1914 that the collected evidence did not support a linear relationship. It was only with the completion of Robert Millikan's famous series of experiments in 1916 that consensus was obtained and Einstein's equation definitively verified.

All these experiments, Millikan's included, were phenomenological.

They aimed at establishing the right (E_m, ν) curve and not the right theory. As mentioned, during most of the period the only serious offer of a theory was Einstein's, but none of the experimentalists concluded in favour of this theory. Most importantly, Millikan's experiment was *not* a confirmation of Einstein's theory. Not only can a confirmation of an equation not be identified with a confirmation of a theory, but, what is more important in this context, Millikan didn't dream of accepting the light quantum theory. On the contrary, as Richardson and Compton had done in 1913, and Hughes in 1914, Millikan used the opportunity to discard 'Einstein's bold, not to say reckless, hypothesis', which fortunately 'now [has] been pretty generally abandoned'.[13] In 1917, in his book *The Electron*, he reaffirmed that Einstein's explanation of the photoelectric effect in terms of light quanta was 'untenable' and 'erroneous'.[14] Most physicists agreed.

Still in 1923 Millikan had not come to terms with the light quantum hypothesis. In his Nobel address of that year he carefully distinguished between Einstein's theory and his equation, and stated that only the latter had been experimentally proved. As far as he was concerned, the photoelectric effect – characteristically described as an 'interchange of energy between ether waves and electrons' – had not yet received a theoretical explanation.[15] This cautious attitude changed of course when soon thereafter Einstein's theory and the photon concept became authorized parts of quantum physics. Now Millikan became celebrated as the one who had discovered experimentally what Einstein had hypothesized, the photon, and very quickly the myth was established that Millikan's experiment confirmed Einstein's theory. Millikan seems to have believed himself in the myth and forgotten about his earlier resistance against the photon. For example, in his autobiography of 1950 he claimed that already in 1915 he realized that his experiments 'simply and irrefutably' proved the truth of Einstein's theory of light quanta.[16] Coming from Millikan's own pen it is not surprising that the myth has been repeated in later textbooks and also in many historical texts. Thus, according to a prominent historian of quantum theory: 'As a result of Millikan's confirmation of Einstein's photoelectric equation, the quantum of action became a physical reality, accessible directly to experiments, and Einstein's conjecture of light quanta was endowed with physical significance and an experimental foundation'.[17]

7. A DILEMMA: NOBLE LIES OR IMMORAL TRUTHS?

As I have indicated, the real history of science is not unambiguously suited for educational purposes. In fact there is an inherent conflict between the aims of history and traditional science education in that the latter needs to present its material in a clear-cut and logical manner which is seldom reflected in the actual course of history. History, in the version of quasi-history, is therefore distorted so as to demonstrate how science ought to be conducted; that is, presented in normative disguise. Whether the educational quasi-history matches the actual history is irrelevant to scientists and textbook authors. As Thomas Kuhn made clear, the historical references make students believe, and are intended to make them believe, that they are participants in a grand historical tradition which has progressed cumulatively and according to definite methodological norms. These norms are of course the norms of modern science:[18]

> Characteristically, textbooks of science contain just a bit of history, either in an introductory chapter or, more often, in scattered references to the great heroes of an earlier age. From such references both students and professionals come to feel like participants in a longstanding historical tradition. Yet the textbook-derived tradition in which scientists come to sense their participation is one that, in fact, never existed. For reasons that are both obvious and highly functional, science textbooks (and too many of the older histories of science) refer only to that part of the work of past scientists that can easily be viewed as contributions to the statement and solution of the texts' paradigm problems.

To put students into situations where they reexperience – or, as the historian and philosopher Robin Collingwood said, 'reenact' – the thoughts of the past, is a legitimate and often fruitful pedagogical method.[19] It is an accepted part of historical research and permeates much of the education in the humanities. But the method requires that the reconstruction of the past is based on facts and is not invented with the purpose of creating a sense of methodological and social tradition which may be fictitious.

In a somewhat different context Stephen Brush and M. Whitaker have called attention to the problematic relationship between history and science education. Brush pointed out that the historical development of science often reveals a picture which is subversive to the aims of science education in the sense that in the real world science has not progressed and scientists not always behaved in pedagogically fit manners.[20] In broad agreement with Brush, Whitaker discussed what he called quasi-history, namely the kind of textbook history which 'is there to provide a framework inside which the scientific facts fit easily, appear to 'make sense' and may be easily remembered for examination purposes'.[21] The way the photoelectric effect is presented in textbooks is clearly an example of such quasi-history. It is an instructive case, but not unique at all. On the contrary, it is quite typical of a large number of textbook standard subjects treated in a more or less historical perspective. They not only distort historical reality, but they do so in a systematic way which supports the scientists' self-understanding and traditions.[22] Uninhibited by historical facts, quasi-history has a practical function by offering historical legitimation for a simplistic methodology and conception of what constitutes good science. In other words, it is ideological.

The fact that textbook versions are usually quasi-historical and serve a legitimizing purpose does not imply that they are consciously distorted. In most cases the authors undoubtedly believe that they have given a fair description of the historical events which they have taken over from existing textbooks, scientists' own accounts, or other sources of a presumably reliable nature. It is important that the historical material presented in science textbooks matches *reasonably closely* with the documented course of the events, i.e., that it does not contradict or grossly distort the authentic history. If it does so, and a historical fable is used instead of the real course of history (which sometimes may be legitimate), the reader has at least a right to be made clearly aware of this. Following the traditional pattern, the widely used *Berkeley Physics Course* introduces quantum theory by referring to three outstanding empirical problems which allegedly plagued physics in the beginning of the twentieth century. These were, it is claimed, Planck's law of blackbody radiation, the stability of atoms, and the photoelectric effect. But then the author of the textbook makes the following exceptional reservation:[23]

> The reader should realize that our discussion is extremely deficient as a historical account: we could not possibly hope to do justice to the very interesting development of quantum physics in a few pages. We are looking at the situation at the beginning of this century in retrospect, and it is then easy to see that these three problems were key problems. However, if we examine the publications for the year 1900 . . . we find that the majority of physicists were concerned with very different things.

This is a very important comment, which adds greatly to an appreciation of the book's historical perspective, but one which is seldom found in science textbooks.

8. THE USE OF CASE-STUDIES

In an educational context, history will necessarily have to be incorporated in a pragmatic, more or less edited way. There is nothing illegitimate in such pragmatic use of historical data so long as it does not serve ideological purposes or violates knowledge of what actually happened. Completeness is, at any rate, a hopeless ideal which cannot even be met in professional history of science. The purist attitude that only detailed, scholarly acceptable history should enter textbooks, amounts in practice to a denial of a historical perspective in science teaching.

The problems of using real history in science teaching need not lead to the pessimistic conclusion that the two are incompatible, and hence that science teachers should either avoid history or rely on quasi-history.[24] A practical solution to the dilemma between historical truth and didactic usefulness in science teaching consists in introducing history in connection with a few carefully selected cases. Then a reliable and fairly detailed historical account may be used to discuss concrete scientific subjects, and it may not be necessary to choose between noble lies and immoral truths.

The case discussed here, the photoelectric effect 1900–1920, is technically simple and easy to document with primary sources. It demonstrates the significance of 'the mistakes, misapprehensions, and altercations . . . [and] all the disputes which have no way contributed to the discovery of truth', which Joseph Priestley would so gladly 'consign to eternal oblivion'.[25] And it is instructive with respect to the interaction between theory and experiment, and the way in which theoretical change takes place. The case is particularly well suited for a discussion of methodological concepts and how these are treated in living science situations. Concepts such as theory, hypothesis, experimental data, prediction, confirmation, and model are central in science and no student should be without a solid knowledge of them. Rather than teaching them in abstract, as were they components of a logical system, or in connection with the artificial version of science included in textbooks, methodological and epistemic concepts can advantageously be discussed as parts of science in action, that is, historically. A case such as the photoelectric effect does not only provide these fundamental concepts with flesh and blood, it also demonstrates that they are parts of a dynamic and often controversial interaction between real scientists.

Although I believe that case-studies of the mentioned type are essential both for philosophical, scientific and educational reasons, they should be used with due reservation. There are important aspects which cannot be illuminated by means of cases, which by their very nature cover a short span of time or a narrow field only. Longer and broader aspects, such as the changes in world views and interaction between different sciences or between sciences and social forces, are not suited for the case method. It may also be worth to point out a potential danger in relying in one's teaching on a few cases. Namely, that they easily, and in educational practice almost unavoidably, will be regarded as representative or exemplaric for the entire development of science. This is a problem which is inherent in any use of examples, and which can only be avoided if the cases are chosen thoughtfully and not allowed to stand alone in the teaching.

NOTES

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1. Parts of the following rely on an earlier paper published in Danish as H. Kragh, 'Fysikhistorie og fysikindlaering: et eksempel', *Gamma* No. 51 (1982), 3–20, and summarized in H. Kragh, 'Physics and History: Noble Lies or Immoral Truths', pp. 70–76 in P. V. Thomsen (ed.), *Science Education and the History of Physics: Proceedings of Munich Conference, 3–9 May 1986*, University of Aarhus, 1986. Other treatments of the history of the photoelectric effect in a didactic perspective include H. Niederer, 'Unterschiedliche Interpretationen des Fotoeffekts. Eine historisch-wissenschaftstheoretische Fallstudie', *Der Physikunterricht* **16** (1982), 39–46, and C. Tarsitani, pp. 165–90 in F. Bevilaqua (ed.), *Storia della Fisica*, Milan: Franco Angeli, 1983. See also K. F. Weinmann, *Die Natur des Lichts. Einbeziehung eines Physikgeschichtlichen Themas in den Physikunterricht*, Darmstadt: Wissenschaftliche Burchgesellschaft, 1980, especially pp. 155–65.
2. D. Steele (ed.), *The History of Scientific Ideas. A Teacher's Guide*, London: Hutchinson, 1970, p. 179.

3. For the history of photoelectric effect and early quantum theory, see, e.g., R. H. Stuewer, 'Non-Einsteinian Interpretations of the Photoelectric Effect', pp. 246–64 in Stuewer (ed.), *Historical and Philosophical Perspectives of Science*, Minneapolis: University of Minnesota Press, 1970; B. R. Wheaton, 'Philipp Lenard and the Photoelectric Effect, 1889–1911', *Historical Studies in the Physical Sciences* **9** (1978), 199–322; Wheaton, *The Tiger and the Shark. Empirical Roots of Wave-Particle Dualism*, Cambridge: Cambridge University Press, 1983, pp. 74–76, 171–90, 234–41; M. J. Klein, 'Einstein's First Paper on Quanta', *The Natural Philosopher* **2** (1963), 57–86; J. Mehra and H. Rechenherg, *The Historical Development of Quantum Theory*, Vol. 1, New York. Springer-Verlag, 1982, pp. 72–83.
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