

## The Oil Drop Experiment: A Rational Reconstruction of the Millikan–Ehrenhaft Controversy and Its Implications for Chemistry Textbooks

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**Abstract:** Research in science education has recognized the importance of history and philosophy of science. Given this perspective, it is important to analyze how general chemistry textbooks interpret Millikan's oil drop experiment. This study has the following objectives: (a) elaboration of a history and philosophy of science framework based on a rational reconstruction of experimental observations that led to the Millikan–Ehrenhaft controversy; (b) formulation of six criteria based on the framework, which could be useful in the evaluation of chemistry textbooks; and (c) evaluation of 31 chemistry textbooks based on the criteria. Results obtained showed that most textbooks lacked a history and philosophy of science framework and did not deal adequately with the following aspects. (a) The Millikan–Ehrenhaft controversy can open a new window for students, demonstrating how two well-trained scientists can interpret the same set of data in two different ways. (b) Millikan's perseverance with his guiding assumption shows how scientists can overcome difficulties with anomalous data. (c) Millikan's methodology illustrates what modern philosophers of science consider important issues of falsification, confirmation, and suspension of disbelief. (d) The experiment is difficult to perform even today, owing to the incidence of a series of variables. (e) Millikan's major contribution consists of discovering the experiment to provide confirmation for the elementary electrical charge. © 2000 John Wiley & Sons, Inc. *J Res Sci Teach*, 37: 480–508, 2000.

Most science educators would consider J.J. Thomson's cathode rays, E. Rutherford's alpha particles, and R.A. Millikan's oil drop experiments to be three of the most important contributions to our understanding of modern chemistry and physics. A recent study (Niaz, 1998) has shown that most general chemistry textbooks emphasize the experimental details of Thomson and Rutherford's experiments and do not mention the heuristic principles on which the experiments were based. For example, in the case of Thomson's cathode rays experiments, the heuristic principle involved the testing of rival hypotheses, determining the mass-to-charge ratio. This helped to identify cathode ray particles as ions or universal charged particles. Thus, the heuristic principle which guides the scientist is more important than the experiment itself.

According to Schwab (1974), scientific inquiry tends to look for patterns of change and relationships, which constitute the "heuristic principles" of our knowledge. In other words,

A fresh line of scientific research has its origins not in objective facts alone, but in a conception, a deliberate conception of the mind . . . this conception [heuristic principle] . . . tells us what facts to look for in the research. It tells us what meaning to assign these facts. (Schwab, 1974, p. 164)

Research in science education has emphasized Schwab's important epistemological distinction between methodological (experimental data) and interpretative (heuristic principles) components (Matthews, 1994; Monk & Osborne, 1997; Niaz, 1998).

Recent studies have shown how both students and teachers (Blanco & Niaz, 1997, 1998) understand, for example, Thomson's experiments as a series of conclusions based on empirical findings (truths). According to Schwab (1962), science cannot be taught as an ". . . unmitigated *rhetoric of conclusions* in which the current and temporary constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24, emphasis in original). It is plausible to suggest that lack of an appreciation of the heuristic principles leads textbooks to present scientific progress as a "rhetoric of conclusions" (cf. Niaz, 1998). Similarly, Kuhn (1970) recognized the impact of textbook presentations on our image of scientific development:

. . . textbooks treat the various experiments, concepts, laws, and theories of the current normal science as separately and as nearly seriatim as possible. . . . From the beginning of the scientific enterprise, a textbook presentation implies, scientists have striven for the particular objectives that are embodied in today's paradigms. (p. 140)

An important aspect of scientific progress is characterized by the finding that the same experimental data can be interpreted by competing frameworks of understanding that clash in the face of evidence (cf. Burbules & Linn, 1991; Lakatos, 1970; McMullin, 1995; Niaz, 1994). Despite this, most general chemistry textbooks follow an approach recommended by Gillespie (1997), viz. "putting observations first." Niaz (1999), on the contrary, argued that in general, the heuristic principle—namely, the conceptual framework/theoretical rationale/presuppositions (Holton, 1978)/guiding assumptions (Laudan, Laudan, & Donovan, 1988)/hard core (Lakatos, 1970) of the scientist are more important than the observations and experimental details.

History of science shows how R.A. Millikan (1868–1953) and F. Ehrenhaft (1879–1952) obtained similar experimental observations, yet their conceptual frameworks (guiding assumptions) led them to postulate the elementary electrical charge (electrons) and fractional charges (subelectrons), respectively. It is essential to emphasize that Millikan and Ehrenhaft approached the same experimental data with entirely different guiding assumptions. The Millikan–Ehrenhaft controversy lasted for many years (1910–1923) and was discussed at scientific meetings by leading scientists such as Max Planck, Jean Perrin, Albert Einstein, Arnold Sommerfeld, Max Born, and Erwin Schrödinger (cf. Holton, 1978, p. 164).

This study had the following objectives:

1. Elaboration of a history and philosophy of science framework based on a rational reconstruction of experimental observations that led to the Millikan–Ehrenhaft controversy
2. Formulation of criteria based on the framework that could be useful in the evaluation of freshman general chemistry textbooks
3. Evaluation of chemistry textbooks using criteria based on the history and philosophy of science framework.

## Millikan's Determination of the Elementary Electrical Charge (Electrons)

### *Millikan's Early Career*

Millikan obtained his doctorate from Columbia in 1895, at the age of 27, with Michael Pupin as his advisor. In 1896, Millikan accepted an invitation from Albert Michelson (famous for the Michelson–Morley experiment), to join the physics department at the University of Chicago. He soon became involved in teaching advanced courses on electron and kinetic theory, and thermodynamics, and at the same time started guiding doctoral students. For the next 10 years at Chicago, Millikan published only one article based on his doctoral thesis and two short notes. On the other hand, he showed considerable interest in the teaching of physics by publishing five introductory textbooks (some of the titles were *A college course in physics*, 1898; and *A laboratory course in physics for secondary schools*, 1907). One of the textbooks (Millikan, Gale, & Edwards, 1928) was used extensively and ran into several editions, and was evaluated by a reviewer in the following terms:

It is written in a clear and simple style, and dogmatic statements are avoided as much as can be without emasculating the whole structure, the result being to stimulate an understanding rather than a memorizing of the subject. (Mendenhall, 1929, p. 106)

In 1908, Millikan became concerned about his research career, as he later recalled in his autobiography (Millikan, 1950, p. 69), and started working on the magnitude of the elementary electrical charge. Apparently, J.J. Thomson's (1897) seminal article on cathode rays had impressed Millikan and started him on this research topic. Besides Thomson, Benjamin Franklin (American folk hero and scientist) was a source of inspiration for Millikan, to whom he attributed the conceptualization of the first electrical particle or atom (Millikan, 1917, p. 15).

### *Millikan's Guiding Assumptions*

An important aspect of Millikan's experiments is that he clearly formulated the guiding assumptions (hard core) of his research program, from the very beginning. Lakatos (1970) characterized the hard core of a research program as the theoretical rationale (heuristic principles) which the scientist does not abandon in the face of anomalous data. It seems that Millikan's research program is a particularly good example of the Lakatosian model.

Millikan (1947) summarized the development of atomic structure at the turn of the century, soon after Thomson's cathode ray experiments, in the following terms (p. 41):

1. What are the masses of the constituents of the atoms torn asunder by X-rays and similar agencies?
2. What are the values of the charges carried by these constituents?
3. How many of these constituents are there?
4. How large are they, i.e., what volumes do they occupy?
5. What are their relations to the emission and absorption of light and heat waves, i.e., of electromagnetic radiation?
6. Do all atoms possess similar constituents? In other words, is there a primordial sub-atom out of which atoms are made?

The sixth question, of course referred to Thomson's finding that the charge to mass ( $e/m$ ) ratio is independent of the gas in the discharge tube. This precisely set the stage for Millikan's determination of the elementary electrical charge ( $e$ ). He outlined his research problem in terms

that can easily be interpreted as his guiding assumption (hard core):

. . . whether the electron which had first made its appearance in Faraday's experiments on solutions and then in Townsend's and Thomson's experiments on gases is after all only a *statistical mean* of charges which are themselves divergent. (Millikan, 1947, p. 58, original italics)

This, of course, implied the existence of the elementary electrical charge ( $e$ ).

At this stage it is important to mention that Millikan (1947) is the second edition of this book, which was first published in 1935. In the preface for the first edition, Millikan pointed out that this could be considered a third revised version of Millikan (1917). In the preface for the second edition (written September 1946), Millikan wrote: "Believing profoundly in the historical approach both in science and its teaching, I have made no changes in the first 400 pages save those necessitated by new knowledge, mostly in the value of units . . ." (p. vii). In those 400 pages, Millikan deals with early views of electricity, electric conductivity in gases, early attempts at determination of the elementary electrical charge, and the atomic nature of electricity.

### *Millikan's Early Experiments*

To understand the genesis of the oil drop experiment and Millikan's ingenuity, it is important to review briefly some of the earlier experiments that attempted to determine the elementary electrical charge ( $e$ ). Millikan (1947) credited Townsend (1897) with having been the first to determine  $e$ . Townsend's method consisted of studying charged clouds of water droplets formed by ionizing (X-rays) air saturated with water vapor. Rate of fall of the cloud under gravity and application of Stokes' law helped Townsend to determine  $e$ , and he reported a mean value of  $e = 3 \times 10^{-10}$  esu. Thomson (1898) was the next to determine  $e$  by a method similar to that of Townsend, and reported a mean value of  $e = 6.5 \times 10^{-10}$  esu. Among other assumptions, Millikan (1947) questioned the following in the Townsend and Thomson studies:

. . . the assumption that the clouds are not evaporating while the rate of fall is being determined is even more serious in Thomson's experiment than in Townsend's, for the reason that in the former case the clouds are formed by a sudden expansion and a consequent fall in temperature, and it is certain that during the process of the return of the temperature to initial conditions the droplets must be evaporating. (p. 53)

Subsequent developments showed that this insight was crucial to Millikan's later success.

Wilson (1903) was the next to determine the elementary electrical charge ( $e$ ), by studying clouds of charged water droplets moving in electrical and gravitational fields. Wilson observed first the rate of fall of the top surface of the cloud between two metal plates under gravity, and later the rate of fall when the electrical field (2000-V battery) as well as gravity were driving the droplets downward. Wilson reported a mean value of  $e = 3.1 \times 10^{-10}$  esu.

Millikan considered Wilson's method a real advance on the previous methods, but nevertheless questioned two major assumptions:

. . . Wilson's method . . . [assumes that] . . . measurements [were] made upon the same droplet, when as a matter of fact the measurements are actually made on wholly different droplets. . . . Furthermore, Wilson's method assumes uniformity in the field between the plates, an assumption which might be quite wide of the truth. (Millikan, 1947, p. 56)

Once again, these insights were crucial to Millikan's later success.

In 1906, Millikan himself repeated Wilson's procedure without any significant improvement and concluded:

Indeed, the instability, distortion, and indefiniteness of the top surface of the cloud were somewhat disappointing, and the results were not considered worth publishing. (Millikan, 1947, pp. 56–57)

Although Millikan's first research experience did not provide satisfactory results, it left him with sufficient insight to design new experiments. Millikan's second attempt (Millikan & Begeman, 1908) provided somewhat better results and were published (mean value of  $e = 4.06 \times 10^{-10}$  esu), but he still worried about the error due to evaporation. A major improvement was the use of a 4000-V battery to reduce the error due to evaporation.

It is important to note that at that time, the research literature considered Rutherford and Geiger's (1908) value of  $e = 4.657 \times 10^{-10}$  esu to be the most probable value. Rutherford and Geiger determined the charge of the alpha particles as  $9.3 \times 10^{-10}$  esu and assumed that it was equal to  $[2e]$ . Hence,  $e$  should have been equal to  $4.65 \times 10^{-10}$  esu.

### *The Balanced Drop Method*

Apparently, the stage was set for a major breakthrough. Millikan outlined his future line of attack:

The plan now was to use an electrical field which was strong enough, not merely to increase or decrease slightly the speed of fall under gravity of the top surface of the cloud, as had been done in all preceding experiments, but also sufficiently to hold the top surface of the cloud stationary, so that the rate of its evaporation could be accurately observed and allowed for in the computations. (Millikan, 1947, pp. 57–58)

In the spring and summer of 1909, Millikan executed this plan with an exceptionally large battery of 10,000 V compared to 4000 V in his previous experiments. This innovation opened a new and unsuspected door. Millikan (1910) expressed the finding in the following terms:

It was not found possible to balance the cloud, as had been originally planned, but it was found possible to do something much better: namely, to hold individual charged drops suspended by the field for periods varying from 30 to 60 seconds. (p. 209)

Application of the powerful field from the 10,000-V dispersed the cloud instantaneously and left a small number of drops, which appeared as distinct bright points. Millikan later recalled in his autobiography:

. . . [the dispersal] seemed at first to spoil my experiment. But when I repeated the test, I saw at once that I had something before me of much more importance than the top surface. . . . For repeated tests showed that whenever a cloud was thus dispersed by my powerful field, *a few individual droplets would remain in view.* (Millikan, 1950, p. 73, original italics)

According to Holton (1978, p. 183), this brought the decade-long technique of measuring electrical charges by the formation of clouds to an abrupt end. These results based on individual wa-

ter droplets were presented at the British Association Meeting held in Winnipeg in August 1909. An abstract was published in the *Physical Review* (December, 1909) and the full paper was published in the *Philosophical Magazine* in February 1910 (Millikan, 1910). Holton (1978, p. 162) considered this to be Millikan's first major publication.

Despite the success of the new method based on observations from individual water droplets, Millikan (1947, p. 66) pointed out the following sources of error: (a) lack of stagnancy in the air through which the drop moved; (b) lack of perfect uniformity of the electric field used; (c) gradual evaporation of the drops—it was difficult to hold a drop under observation for more than a minute; and (d) validity of Stokes' law. To avoid these errors and refine his method, Millikan designed the oil drop experiment.

### *The Oil Drop Experiment*

To avoid the error due to evaporation, Millikan replaced water with oil and conducted a series of studies, of which the one published in 1913 was considered by Holton (1978, p. 202) to be the most authoritative. Millikan (1950) later recalled that the idea of using oil instead of water occurred to him suddenly while he was riding the train back to Chicago from the Winnipeg meeting in August 1909 (p. 75). Millikan (1913, p. 121) reported a series of improvements: (a) The drag which the medium exerts upon a drop is unaffected by its charge; (b) oil drops act essentially like solid spheres; (c) density of the oil drops is the same as that of the oil in bulk; (d) correction term for Stokes' law; (e) more perfect elimination of convection; and (f) improved optical system. The paper presented a complete summary of data on 58 drops studied over 60 consecutive days. Mathematically, Millikan started with the following equation:

$$v_1/v_2 = mg/Fe - mg$$

With appropriate substitutions, the equation takes the following form:

$$e_n = 4/3 \pi (9\mu/2)^{3/2} \{1/g(\sigma - \delta)\}^{1/2} (v_1 + v_2) v_1^{1/2}/F \dots \quad (1)$$

Including the correction from Stokes' law gives the equation:

$$v_1 = 2/9 g a^2 (\sigma - \delta)\mu \{1 + A l/a\} \quad (2)$$

Combining Equations (1) and (2) gives the value of  $e$ :

$$e (1 + A l/a)^{3/2} = e_n$$

where  $v_1$  = speed of descent of the drop under gravity;  $v_2$  = speed of ascent of the drop in the electric field;  $mg$  = force of gravity;  $F$  = electric field;  $e_n$  = frictional charge on the drop;  $\mu$  = coefficient of viscosity of air;  $\sigma$  = density of the oil;  $\delta$  = density of air;  $a$  = radius of the drop;  $l$  = mean free path of a gas molecule; and  $A$  = correction term constant. Mean value obtained with this method was reported to be:  $e = 4.774 \pm 0.009 \times 10^{-10}$  esu. At this stage, it is important to note that Millikan, based on his guiding assumptions, expected the value of  $e_n$  to be an integral multiple of  $e$ , where  $n = 1, 2, 3, \dots$ . Apparently, guided by his assumptions, Millikan discarded values that did not turn out to be integral multiples. This was the main cause of the controversy with Ehrenhaft and will be dealt with in the next section.

Millikan (1913) summarized the new method in the following terms:

The essential feature of the method consisted in repeatedly changing the charge on a given drop by the capture of ions from the air and in thus obtaining a series of charges with each drop. These charges showed a very exact multiple relationship under all circumstances—a fact which demonstrated very directly the *atomic structure of the electric charge*. (p. 109, emphasis added)

### Ehrenhaft's Determination of Fractional Charges (Subelectrons)

#### *Ehrenhaft's Early Career*

Ehrenhaft studied at the University of Vienna and the Institute of Technology at Vienna. He was accepted as privatdocent at the University of Vienna in 1905 and was teaching statistical mechanics by 1909. He was known for his experimental study of Brownian motion in gases, which he built on the theoretical ideas of Einstein and von Smoluchowski. For this work he received the Lieben Prize of the Vienna Academy of Sciences in 1910. In 1912 he was appointed Associate Professor at the University of Vienna. Among other prominent scientists, he was on friendly terms with Einstein.

Ehrenhaft was about 10 years younger than Millikan, and by 1910 (the year of Millikan's first major publication) was a fairly established figure in the European scientific elite and had about 10 publications (the first in 1902) on what he referred to as the "elementary quantum of electric charge."

#### *Ehrenhaft's Experimental Work*

Ehrenhaft's experimental determination of electrical charges was based on preparation of colloids and the ultramicroscopic Brownian movement observations of individual fragments of metals such as those from the vapor of a silver arc (Ehrenhaft, 1902).

By measuring the motions of colloidal particles with and without an horizontal electrical field and applying Stokes' law, he measured the charges on the particles (Ehrenhaft, 1909a). In contrast to Millikan, at this stage, he did not use a vertical electrical field. A major shortcoming of this method was that his observations were based on two different drops, one for observing the particles without the electrical field and the other with the electrical field. Ehrenhaft's value of  $e$  ( $4.6 \times 10^{-10}$  esu) is far closer to Rutherford's ( $4.65 \times 10^{-10}$ ) and Planck's ( $4.69 \times 10^{-10}$ , from blackbody radiation) than that of Millikan and Begeman (1908). Holton (1978) considered Ehrenhaft's (1909) determination of the electrical charge to be the first study in the literature that was based on individual charged particles. Nevertheless, Holton (1978) clarified: "Following this procedure [Ehrenhaft's],  $e$ , therefore, cannot be the charge determined on a single object but must be an average" (p. 187). Apparently, in studies conducted by Ehrenhaft until 1909, he accepted the elementary electrical charge as his guiding assumption.

In contrast, starting in 1910, Ehrenhaft (1910a) conducted new studies in which he used a vertical electrical field strong enough to make particles rise against gravitation (similar to Millikan's method). Ehrenhaft reported results based on platinum and silver particles from arcs, which astounded the scientific community. The 22 measurements of charge ranged from  $7.53 \times 10^{-10}$  esu down to  $1.38 \times 10^{-10}$  esu. Ehrenhaft reported that these findings could not be explained owing to inadequacies in method, but rather led to the conclusion that if an elementary electrical charge does exist, its value must be considerably lower. According to Holton (1978):

A counter challenge was thus issued to all believers in  $e$  as the quantum of charge for which nothing in theory or experiment seemed to have prepared the ground. Out of the blue, the subelectron had appeared on the stage. (p. 198)

Soon after this (Ehrenhaft, 1910a, published April 21, 1910), Ehrenhaft (1910b, published May 12, 1910) coined the word *subelectron* and announced that his studies indicated that indivisible quantities of electric charge do not exist in nature at the level of  $>1 \times 10^{-10}$  esu.

### Millikan–Ehrenhaft Controversy

The controversy did not start on April 21, 1910 (publication of Ehrenhaft, 1910a), but in February 1910 with the publication of Millikan's (1910) first major article published in *Philosophical Magazine*.

#### *Millikan's Critique of Ehrenhaft's Method*

Millikan (1910) presented a mean value of the elementary electrical charge to be  $4.69 \times 10^{-10}$  esu, which came close to that of Rutherford and Geiger (1908), viz.  $4.65 \times 10^{-10}$  esu. In that article, Millikan also critically evaluated the values obtained by other investigators and rejected four of those, including one by Ehrenhaft (1909b). Interestingly, the mean value of Ehrenhaft ( $4.6 \times 10^{-10}$  esu) came close to that of Millikan, and yet he rejected it for the following reasons (Millikan, 1910, p. 226):

1. Stokes' law was applied without modification to very small particles (drops) of doubtful sphericity.
2. Velocity measurements were not made on one and the same particle, but were mean values of observations.
3. Radii of the particles were determined in a dubious manner.
4. No provision was made for the possibility that multiple charges may be carried by some of the particles.

Strangely, the first and the fourth criticisms were also applicable to Millikan's own work in 1910. Furthermore,

... he [Millikan] was rejecting a confirmatory value, one obtained by an established researcher who had used a method closer to his own than the methods of others whom Millikan was not rejecting. (Holton, 1978, p. 192)

As the controversy heated up, Millikan and colleagues brought forward even more serious reservations, such as the density of the metal particles and the role of Brownian movement (cf. Millikan & Fletcher, 1911; Millikan, 1916, 1917).

#### *Ehrenhaft's Critique of Millikan's Method*

Ehrenhaft (1910a) entered the fight over the electron and continued to report lengthy studies, often with new data and a running controversy with Millikan, until his last article on the subject (Ehrenhaft, 1941). However, what is interesting is Ehrenhaft's (1910b) first major attack on Millikan's method. In that article, Ehrenhaft closely scrutinized Millikan's (1910) data. He recalculated the charge on each drop from each of Millikan's observations separately. Millikan



(1910), in contrast, used average values of times of ascent and descent, measured on different droplets. Ehrenhaft's calculations produced a large spread of values of the elementary electrical charge, ranging from  $8.60 \times 10^{-10}$  esu to  $29.82 \times 10^{-10}$  esu. Furthermore, Ehrenhaft showed how Millikan's method led to paradoxical situations. For example, a drop with a charge of  $e_n = 15.59 \times 10^{-10}$  esu had been placed among those assumed to be carrying three electrons (i.e.,  $n = 3$ ), whereas another drop with a charge of  $e_n = 15.33 \times 10^{-10}$  esu was assumed to be carrying four electrons ( $n = 4$ ). How do we explain these differences?

Holton (1978) provides the following insight on the impasse:

It appeared that the same observational record could be used to demonstrate the *plausibility of two diametrically opposite theories*, held with great conviction by two well-equipped proponents and their respective collaborators. Initially, there was not even the convincing testimony of independent researchers. (pp. 199–200, emphasis added)

Testimony of independent researchers tended to favor Millikan. Major support for Millikan came from E. Warburg, H. Rubens, W. Wien, J. Perrin, and Einstein at the Solvay Congress of 1911 (cf. Holton, 1978, p. 200). Nevertheless, the controversy among Millikan, Ehrenhaft, and their collaborators continued for many years.

### *Development of the Controversy*

The controversy between the two parties was intense. Ehrenhaft wrote about a dozen articles in the following 4 years, all implicitly aimed at discrediting Millikan's measurements. Millikan also wrote extensively and rebutted Ehrenhaft's criticisms. Most of the arguments by both parties were repetitious. For the sake of brevity, arguments from Millikan (1916) which are representative of the controversy are presented here.

Millikan (1916) first responded to Ehrenhaft's (1910b) criticism with respect to having used average values of times of ascent, descent, and other parameters in the following terms:

What I actually did was neither more nor less than is always done in obtaining an accurate measurement of any physical magnitude, for example, a length, namely to make exactly the same measurement several times over, and then take a mean solely *for the sake of diminishing the error in reading the measuring instrument*. This instrument was in my case a stopwatch. There was not the slightest reason for considering the fluctuations which Professor Ehrenhaft found in my measurement of  $e$  as arising from varying values of the ionic charge, since they were no larger than the necessary fluctuations in a stopwatch measurement of an interval from 2 to 5 seconds in length. Had I worked out  $e$  for each individual reading and then taken the mean my result would of necessity have come out exactly as it did. The point raised has to do, therefore, merely with the way in which I tabulated my data, not at all with the way in which I made my measurements, *which were in fact measurements upon the charge carried by individual particles*. (Millikan, 1916, p. 508, original italics)

This shows that Millikan went to considerable length to rebut Ehrenhaft's (1910b) criticism, and yet left the main issue unanswered, viz. why did the calculation by Ehrenhaft (1910b) of the elementary electrical charge from individual droplets (based on Millikan's data) give such a wide spread of values? Later it will be seen that this line of argument was not Millikan's best defense.

Next in that article, Millikan (1916) addressed the issues raised by a new publication of Ehrenhaft (1914) in which he had obtained considerably lower values of  $e$  based on the Brown-

ian movement of mercury and gold droplets. Ehrenhaft seemed to be suggesting that their droplets were much smaller than those of Millikan and their lower values of  $e$  were a function of the radius of the drop. Millikan raised the following objections to Ehrenhaft's new data:

1. While obtaining the mercury droplet from an electric arc an oxide was deposited on the droplet, which decreased the density of mercury. Thus, if the density of the drop were lower than the assumed density, the calculated value of  $e$  would be lower.
2. Millikan questioned the sphericity of the mercury droplets and hence the application of Stokes' law. Ehrenhaft had countered that he had photographed the droplets and found them to be spherical. Millikan rejected this evidence: ". . . *the particles in question are not those which he photographs, for these are far below the limit of resolving power of any optical instrument*" (p. 615, original italics).
3. Based on some of his own data on mercury droplets, Millikan also rejected the claim that the value of  $e$  decreased with a decrease in radius of the droplets.
4. Error due to evaporation of mercury droplets: Millikan presented some of his own data to show that mercury droplets evaporated even more rapidly than oil.
5. Finally, Millikan concluded: "In a word then Ehrenhaft's tests as to sphericity and purity are all quite worthless . . . the data itself is so erratic as to render discussion of it needless" (p. 615).

Despite the merit of these arguments, Millikan presented his most convincing argument at the end. Millikan asked the reader to suppose that Ehrenhaft's data were free of all the possible errors that had been discussed previously, and posed the following dilemma:

That these same ions have one sort of charge when captured by a big drop and another sort when captured by a little drop is obviously absurd. If they are not the same ions which are caught in the two cases, then, *in order to reconcile the results with the existence of the exact multiple relationship . . . , it would be necessary to assume that there exist in the air an infinite number of different kinds of ionic charges corresponding to the infinite number of possible radii of drops, and that, when a powerful electric field drives all of these ions toward a given drop, this drop selects in each instance just the charge which corresponds to its particular radius.* Such an assumption is not only too grotesque for serious consideration but is directly contradicted by my experiments. . . . (Millikan, 1916, p. 617, original italics)

This passage is indeed revealing. In summary, Millikan is telling the reader that experimental observations are important, but there is something even more important, viz. the guiding assumptions, and any data that go against them would appear to be "absurd" and "grotesque," and hence subelectrons could not exist.

### The Controversy in Retrospect

For many years, scientists were puzzled by the Millikan–Ehrenhaft controversy, just as the readers of this article must be feeling uneasy. Support for Millikan's position was not spontaneous and many leading physicists withheld judgment. H.A. Lorentz in the 1916 edition of *The theory of electrons* stated,

Millikan has found values for  $e$  which can be considered as multiples of a definite "elementary" charge. Ehrenhaft, however, has been led to the conclusion that in some cases the charges are not multiples of the elementary one and may even be smaller than it. The question cannot be said to be wholly elucidated. (Lorentz, 1952, p. 251)

Although in 1923 Millikan was awarded the physics Nobel prize, as late as 1922, R. Bär in a review of the controversy conceded: “The experiments [Ehrenhaft’s] left, at the very least, an uncomfortable feeling” (Bär, 1922). Indeed, Holton (1978) pointed out that “. . . there was never a direct laboratory disproof of Ehrenhaft’s claims” (p. 220).

A new dimension to the controversy was added by Holton’s (1978) discovery of Millikan’s two laboratory notebooks in his Archives at the California Institute of Technology, Pasadena. These notebooks have raw data and some of the data reduction procedures used in his *Physical Review* article (Millikan, 1913). Ehrenhaft’s notebooks, however, were lost in the Second World War, when he had to emigrate to the United States after the Nazi occupation of Austria.

### *Critical Evaluation of Millikan’s and Ehrenhaft’s Methods*

The Millikan notebooks (October 28, 1911, to April 16, 1912, about 175 pages) are indeed a rare opportunity to see a scientist working in his laboratory. Furthermore, the controversy over the existence of the electron was in full swing and Millikan was then a mature scientist.

Millikan’s procedure seems to have consisted of making a rough calculation for the value of  $e$ , as soon as the data for the times of descent/ascent of the oil drops started coming in. Holton (1978, p. 207) reproduced the data in Millikan’s handwriting from one of the 140 experiments that are included in the notebooks. Apparently, this was an experiment that did not give the value of  $e$  that Millikan was expecting, and he noted frankly: “*Error high* will not use . . . can work this up & probably is ok but point is [?] not important. Will work if have time Aug. 22.” Holton (1978) remarked on this experiment:

It was a failed run—, or *effectively, no run at all*. Instead of wasting time investigating it further, he simply went on to make another set of readings with a new drop, recorded on the next page of the notebook. (p. 209)

Now let us turn to the actual publication (Millikan, 1913). Millikan meticulously presented complete data on 58 drops and emphasized,

*It will be seen from Figs. 2 and 3 that there is but one drop in the 58 whose departure from the line amounts to as much as 0.5 percent. It is to be remarked, too, that this is not a selected group of drops but represents all of the drops experimented upon during 60 consecutive days . . .* (Millikan, 1913, p. 138, original italics)

How do we interpret this information? The laboratory notebooks tell us that there were 140 drops and the published results are emphatic that there were 58 drops. What happened to the other 82 drops? Herein lies the crux of the difference in the methodologies of Ehrenhaft and Millikan. Holton (1978) speculated about Ehrenhaft’s response if he had had access to Millikan’s notebooks:

If Ehrenhaft had obtained such data, he would probably not have neglected the second observations and many others like it in these two notebooks that shared the same fate; he would very likely have used them all. (pp. 209–210)

At this stage, it is important to note that Ehrenhaft, too, obtained data that he interpreted as integral multiple of the elementary electrical charge ( $e$ ). Nevertheless, his argument was precisely that there were many drops that did not lead to an integral multiple of  $e$ .

The question we need to answer at this stage is, what was the warrant under which Millikan discarded more than half of his observations? The answer is simple but not found frequently in the research literature, and much less in chemistry textbooks. Millikan's guiding assumptions provided the warrant. Indeed, Millikan would perhaps have liked to warn Ehrenhaft that all the readings cannot be used as their experiments were constantly faced with difficulties such as evaporation, sphericity, radius, and change in density of droplets due to oxides or dust particles, and variation in experimental conditions (battery voltages, stopwatch errors, temperature, pressure, convection, and so on).

Interestingly, even before the controversy had started, Millikan, his first major publication (1910), had used a system for classifying the merit of his observations:

The observations marked with a triple star are those which were marked "best" in my notebook. . . . The double-starred observations were marked in my notebook "very good." Those marked with single stars were marked "good" and others "fair." (p. 220)

There were 38 sets of observations in this study, of which 2 were three-starred, 7 double-starred, 10 single-starred, 13 no star (i.e., fair), and 6 had been discarded altogether. Holton (1978) considered this disclosure to border on idiosyncratic frankness and added:

Only the internal ethos of science, which prizes the fullest disclosure of data, seems to have motivated him [Millikan] to mention this set of discarded observations. (p. 193)

With respect to the set of discarded observations, Millikan (1910) himself acknowledged:

Although all of these observations gave values of  $e$  within 2 per cent. of the final mean, the uncertainties of the observations were such that *I would have discarded them had they not agreed with the results of the other observations*, and consequently I felt obliged to discard them as it was. (p. 220)

Holton (1995), while reviewing the evidence, concluded: "Throughout, an air of utter self-confidence pervades the paper" (p. 152). Not surprisingly, later in his publications, Millikan refrained from making such disclosures.

At this stage it is important to differentiate between the design and the discovery of the oil drop experiment (Holton, 1978, pp. 184–185). Millikan evidently did not design the experiment, but discovered it. In other words, the experiment can be performed (design) without alluding to the electron theory, viz. the guiding assumptions. How would that have contributed to our existing knowledge? It was the electron theory which suggested the existence of the elementary electrical charge and hence the need for its experimental determination. The importance of Millikan's contribution is enhanced even further if we concur with Nagel (1961):

It is unlikely that Millikan (or any one else) would have devised [discovered] the oil-drop experiment if some atomistic theory of electricity had not first suggested a question that seemed important in the light of the theory and that the experiment was intended to settle. (p. 90)

Van Fraassen (1980) agreed that Millikan discovered the experiment, but added, ". . . he [Millikan] was writing theory by means of his experimental apparatus" (p. 77). Achinstein (1991, pp. 331–333), on the other hand, argued (despite the evidence to the contrary) that it was the experiment that led Millikan to postulate the elementary electrical charge.

### *Suspension of Disbelief*

Holton (1986) recognized that science education does not recommend Millikan's methodology with respect to the oil drop experiment to our "beginning students" (p. 12). On the contrary, textbooks and laboratory manuals inculcate the scientist's standard of objectivity and a de-personalized attitude toward experimental data, often referred to as the scientific method. Holton (1978) suggested that every novice be taught that "... the graveyard of science is littered with those who did not suspend belief while the data were pouring in" (p. 212). The textbook strategy obviously does not present to the students the other side of the coin, which can be referred to as suspension of disbelief—that is,

... the scientist's ability during the early period of theory construction and theory confirmation to hold in abeyance final judgments concerning the validity of apparent falsifications of a promising hypothesis. (Holton, 1978, p. 212)

The role of falsification has been the subject of considerable debate in the philosophy of science literature. Popper (1962), for instance, considered the scientific attitude to look not for verifications, but for crucial tests that can lead to the falsification of a theory. Lakatos (1970), on the other hand, emphasized the importance of rivalry between competing theoretical frameworks (guiding assumptions) for explaining the same experimental findings. Furthermore, Lakatos showed that scientists generally do not abandon their guiding assumptions in the face of anomalous data. According to Giere (1988):

... Lakatos turned Popper's falsificationist methodology on its head. For Popper, confirmations count for little; refutations are what matter. For Lakatos, refutations count for little; confirmations are what matter. (p. 39)

Millikan's methodology consisted precisely in not abandoning his guiding assumptions despite anomalous data (values of charges on the droplets that were not integral multiples of  $e$ ), just as the Lakatosian (1970) scheme would have suggested. On the other hand, Millikan looked for confirmations that verified his guiding assumption (values of charges on droplets that were integral multiples of  $e$ ).

### *Millikan and the Nobel Prize*

The Nobel Committee for Physics showed vision and foresight by awarding the prize to Millikan in 1923, as the controversy was not entirely over. The prize was awarded for Millikan's work on the elementary charge of electricity and the photoelectric effect. Nevertheless, the Committee left no doubt as to the importance of the first contribution, when A. Gullstrand (Chairman of the Committee) in his three-page presentation speech devoted only the last six lines to the photoelectric effect. The Committee endorsed Millikan's research program to such a degree that it seemed that many passages might have been written by Millikan himself. Following is an example:

Millikan's aim was to prove that electricity really has the atomic structure, which, on the base of theoretical evidence, it was supposed to have. To prove this it was necessary to ascertain, not only that electricity, from whatever source it may come, always appears as a unit of charge or as an exact multiple of units, but also that the unit is not a statistical mean, as, for instance, has of late been shown to be the case with atomic weights. (Gullstrand, 1965, p. 52)

Millikan himself summarized his contribution in extremely lucid terms:

Indeed, Nature here was very kind. She left only a narrow range of field strengths within which such experiments as these are all possible. They demand that *the droplets be large enough so that the Brownian movements are nearly negligible, that they be round and homogeneous, light and non-evaporable, that the distance be long enough to make the timing accurate, and that the field be strong enough to more than balance gravity by its pull on a drop carrying but one or two electrons.* Scarcely any other combination of dimensions, field strengths and materials, could have yielded the results obtained. (Millikan, 1965, pp. 57–58, emphasis added)

Indeed, Millikan had summarized his experiments and vicissitudes of the previous 15 years in cogent terms. At the same time Millikan was not oblivious of the larger audience, history, and Ehrenhaft when he added:

After ten years of work in other laboratories in checking the methods and the results obtained in connection with the oil-drop investigation published from 1909 to 1923, there is practically universal concurrence upon their correctness, *despite the vigorous gauntlet of criticism which they have had to run.* (Millikan, 1965, p. 60, emphasis added)

In order not to leave any doubt that he was referring to Ehrenhaft, he next posed the following question: “Shall we ever find that either positive or negative electrons are divisible?” (p. 60). In a truly scientific spirit, Millikan perhaps even made a concession to the perseverance and contribution of Ehrenhaft, by responding to the question himself:

If the electron is ever subdivided it will be probably be because man, with new agencies as unlike X-rays and radioactivity as these are unlike chemical forces, opens up still another field where electrons may be split up without losing any of the unitary properties which they have now been found to possess in the relationships in which we have thus far studied them. (Millikan, 1965, p. 61),

### *Ehrenhaft, Subelectrons, and Quarks*

Both Ehrenhaft and Millikan found fractional charges that were  $1/3e$ ,  $2/3e$ ,  $1/10e$ , and so on. Millikan attributed these fractional charges to experimental errors, whereas Ehrenhaft used these results to deny the existence of the elementary electrical charge. Interestingly, modern physics has found various subatomic particles and one of these, a quark would have two thirds the charge of the electron. This raises a question as to the possibility that Ehrenhaft and Millikan might have been observing quarks. P.A.M. Dirac (1977), after studying the experimental conditions under which Ehrenhaft and Millikan worked, concluded: “This does not constitute evidence for quarks. It merely shows there was some experimental error, perhaps the same for both of them [Ehrenhaft and Millikan], affecting their smaller particles” (p. 293).

### *Intellectual Milieu of the Controversy*

Millikan's doctoral thesis advisor, Pupin told him that he did not believe in the kinetic theory at all, and according to Holton (1978): “If Millikan had followed Pupin's example, he could have supported a rival theory of electricity, based on the thematic concept of the continuum [ether] rather than on the thematic concept of atomism” (p. 179). The rivalry between the ether and the atomic theorists in the late 19th and the early 20th century forms an important backdrop

for the understanding of Ehrenhaft's and Millikan's methodologies. Ernst Mach, Wilhelm Ostwald, George Helm, and Pierre Duhem were the leading phenomenologists (ether theorists) who rejected all forms of the atomic hypothesis, espoused by J.C. Maxwell, M. Planck, J. Perrin, and A. Einstein. According to the former electricity was a continuous homogeneous liquid, whereas the latter considered it to consist of discrete atomic particles and hence the importance of the elementary electrical charge.

Early in his career, Millikan was influenced by Benjamin Franklin's hypothesis of the atomic nature of electricity, and in some of his early physics textbooks he recognized Franklin's contribution. The atomic hypothesis formed an important part of Millikan's guiding assumptions.

Ehrenhaft espoused the atomic hypothesis in his early publications (before April 21, 1910), and some of his papers explicitly referred to the "elementary quantum of electrical charge." After that, he interpreted his experimental findings to show that such a hypothesis was not tenable. According to Holton (1978), it is difficult to explain this change in Ehrenhaft's guiding assumptions. It could have been Millikan's (1910) rejection of his determination of the electrical charge (discussed earlier) or it could have been the influence of the antiatomists on the Continent, including Mach himself. In Ehrenhaft's later publications, ". . . there was increasingly an epistemological component . . . that is, the use of his experiments to attack the credibility or necessity of atomism itself" (Holton, 1978, p. 219).

Finally, Ehrenhaft seemed to be responding to Millikan's Nobel prize speech at a public ceremony held in a public park in Vienna in 1925 to unveil a bust to commemorate the 10th anniversary of Mach's death, when he declared:

Mach [appears] as an advocate of the much more modest, phenomenological point of view which finds satisfaction merely with the description of the phenomena and despairs of other possibilities. The others are advocates of views that through statistical methods and speculative discussions concerning the constitution of matter, are reflected in atomism. (Neue Freie Presse, Vienna, 12 June 1926 (Suppl), p. 12. Reproduced in Holton, 1978, p. 221)

A recent appraisal of the controversy has recognized the role of both Ehrenhaft and Millikan:

. . . Millikan's personal triumph over Ehrenhaft should not be construed to represent the unmitigated superiority of his experimental philosophy, for, indeed, the selection of data without the experimental perspicacity showed by Millikan borders closely on scientific fraud. In each man, therefore, are represented scientific attitudes that are necessary attributes of sound scientific practice. (Silverman, 1992, p. 169)

Interestingly, on reading an earlier version of this article, Gerald Holton (1999) presented his reappraisal of the controversy in the following terms:

. . . Millikan regarded the drops he neglected as unfulfilled, "aborted" sorts of events on which he thought he need not waste his time to find out what is wrong. (And many things can and do go wrong to prevent a "reading" to become a "datum"). That is, as I say, not how we do science now. But "fraud" is all too easy to cry out now! [Also note] . . . Millikan's final value for  $e$  could not be improved by anyone for many years.,

#### Millikan–Ehrenhaft Controversy and Science Education

Laudan (1996) considered the sciences to be much more tightly bound to their history than other intellectual activities (p. 153). This history is intertwined with the topics of study, so that

. . . the budding chemist learns Prout's and Avogadro's hypotheses, and Dalton's work on proportional combinations; he learns how to do Millikan's oil drop experiment; he works through Linus Pauling's struggles with the chemical bond. (Laudan, 1996, p. 153)

Although Laudan's concept of the role of history in science education is laudable, recent research in science education has shown that this role is at best similar to what Schwab (1962) referred to as a "rhetoric of conclusions" (cf. Matthews, 1994; Monk & Osborne, 1997; Niaz, 1998).

Arons (1990) considered Millikan's oil drop experiment to be adequately treated in many textbooks, and that there is no need for detailed elaboration (p. 239). Nevertheless, he raised an important issue by pointing out that many textbooks state that "Millikan measured the charge on the electron" (p. 239). Later, Arons (1990) clarified this:

What Millikan did was measure the size of the elementary charge as it was to be observed, accreted on oil droplets, in an ionized gas. Although some of the ions might have been electrons, most were probably not. (p. 240)

Holton (1978) also made the same point:

Strictly speaking, his [Millikan's] experiments showed not that the elementary charge of electricity itself had to be atomic, but only (as he was aware) that the transfer of charges to and from small material bodies occurred in integral multiples of  $e$ . (p. 184)

Matthews (1994) continued by pointing out that epistemologically, what is important is not the experiment itself but rather the Millikan–Ehrenhaft controversy. He considered the controversy to be yet another chapter in the long struggle between theoretical entities (Millikan's elementary electrical charge) and experimental facts (Ehrenhaft's findings). Matthews (1994) concluded:

In Millikan's case we have another clear example of the theoretical objects governing the empirical object and the interpretation of its measurement. As with Galileo, there is nothing unscientific about this; it may not accord with empiricist orthodoxy, but this orthodoxy champions del Monte and Ehrenhaft, not Galileo and Millikan. (p. 124)

At this stage, it is important to note that science teachers' overdependence on textbooks is widespread in most parts of the world, including the United States (Weiss, 1993). Similarly, the role of textbooks in teaching the nature of science has been recognized in the history and philosophy of science literature (McComas, Almazroa, & Clough, 1998). Thus, it is plausible to suggest that undergraduate general chemistry textbooks can go beyond their actual presentations (mostly rhetoric of conclusions) by including some aspects of the Millikan–Ehrenhaft controversy, guiding assumptions, falsification, confirmation, and suspension of disbelief.

### *The Oil Drop Experiment in the Undergraduate Laboratory*

Millikan's oil drop experiment has been performed in the undergraduate physics laboratory, with commercially produced apparatus (Olson, 1965; Anderson, 1966). Kruglak (1972) cautioned: ". . . important as it may be for a physical science major to get experience with the oil-drop apparatus, the overemphasis on getting a "good" value of  $e$  might be pedagogically counterproductive" (p. 769). Based on results obtained from a student survey, Kruglak (1972)



considered the experiment to be the most frustrating in the undergraduate laboratory. Nevertheless, “. . . few experiments epitomize better for students the experimental method and develop an empathy for the challenges and vicissitudes of the physicist” (Kruglak, 1972, p. 769).

Heald (1974) mentioned that a major difficulty with the experiment is the possibility of bias in the selection of “suitable” drops, and the philosophical problems of dealing with data that violate one’s preconceptions (p. 245). Kapusta (1975) referred to a dilemma faced by Millikan himself:

The important variables that are measured are the rise and fall times of the drop moving through a known distance. Some of the drops have much higher velocities than others. Should one choose to observe the fast drops, the slow drops, or those of intermediate velocities? (p. 799)

The author suggests that after performing many experiments, the best results were obtained when the measuring times were on the order of 10 s.

It appears that the oil drop experiment, when used in the laboratory with these criteria (all the drops cannot be used, measuring times will have to be selected, noisy data, and so on), can be considerably helpful to students in understanding the complexities of scientific progress.

#### Criteria for Evaluation of Chemistry Textbooks

Based on a history and philosophy of science perspective (rational reconstruction) presented in the previous sections of this article, here we present criteria for the evaluation of freshman/college level general chemistry textbooks:

1. *Millikan–Ehrenhaft controversy*: Millikan and Ehrenhaft obtained similar experimental results and yet the two interpreted their findings within different theoretical frameworks (guiding assumptions). The controversy started in 1910 with Millikan’s critique of Ehrenhaft’s method. The controversy turned into a bitter dispute for the next 15 years. According to Millikan, there existed an elementary electrical charge and charges on all droplets were integral multiples of this fundamental charge. Ehrenhaft argued that the charges on the droplets varied widely, and hence the existence of an elementary electrical charge could not be sustained. This criterion is based on Dirac (1977), Ehrenhaft (1910a, 1910b, 1914, 1941), Holton (1978), and Millikan (1910, 1913, 1916, 1917, 1947).
2. *Millikan’s guiding assumption*: Drawing inspiration from Franklin, Faraday, Stoney, Thomson, and others, Millikan formulated the guiding assumption of his research program early in his career. According to this guiding assumption, based on the atomic nature of electricity, Millikan hypothesized the existence of an elementary electrical charge. In his experiments, Millikan found droplets with a wide range of electrical charges. Despite such anomalous data, if it were not for the guiding assumption, Millikan would have abandoned the search for the elementary electrical charge. This criterion is based on: Holton (1978) and Millikan (1910, 1913, 1916, 1917, 1947).
3. *Suspension of disbelief*: An important characteristic of Millikan’s methodology was to hold the falsification of his guiding assumption in abeyance—that is, suspension of disbelief. In contrast to the traditional scientific method inculcated in school science, Millikan’s methodology has found support in modern philosophy of science. This criterion is based on Holton (1978), Lakatos (1970), and Millikan (1913, 1916, 1917).
4. *Transfer of charge as an integral multiple of the elementary electrical charge*: Millikan did not measure the charge on the electron itself, but rather the transfer of charge on

droplets as an integral multiple of the elementary electrical charge ( $e$ ). This criterion is based on Arons (1990), Holton (1978), and Millikan (1917).

5. *Dependence of the elementary electrical charge on experimental variables*: The oil drop experiment is extremely difficult to handle. Millikan was constantly trying to improve his experimental conditions to obtain the charge on the droplets as an integral multiple of the elementary electrical charge. Some of the variables that he constantly referred to were evaporation, sphericity, and radius of the droplets, change in density of the droplets, changes in battery voltages, temperature, and viscosity of the air. The oil drop experiment is still difficult to perform in the laboratory. A comparison of Millikan's laboratory notebooks and published results showed that given the complexity of the experimental conditions, he discarded droplets that did not have velocities within a certain range. This criterion is based on: Holton (1978) and Millikan (1913, 1916, 1965).
6. *Millikan's experiments as part of a progressive sequence of heuristic principles*: Millikan's work started by repeating and a critical evaluation of the experimental work of Townsend, Thomson, and Wilson on charged clouds of water droplets. The first progressive transition was the balanced drop method by using a sufficiently strong electrical field, which later led to the oil drop experiment. It can be argued that Millikan did not design the experiment, but rather discovered it. This criterion is based on Holton (1978) and Millikan (1910, 1913, 1917, 1950).

The following classifications were elaborated to evaluate the textbooks:

- Satisfactory (S): Treatment of the subject in the textbook is considered to be satisfactory, if the criterion is described and educational implications are drawn.
- Mention (M): A simple mention of the criterion, without explicit elaboration.
- No mention (N): No mention of the issues involved in the criterion.

To implement the criteria, a university professor with a doctorate in chemistry and 25 years of teaching experience at both the freshman and higher levels, and the author applied the criteria separately to evaluate three textbooks (selected randomly). The university professor had done some work in history and philosophy of science and was provided with the complete manuscript (except the section on evaluation) and the salient aspects of the controversy were discussed before application of the criteria. Both evaluators coincided on the evaluation of four criteria (of six) on the first and second textbooks and five criteria on the third textbook. Each evaluator explained the points of disagreement, and after discussion, consensus was achieved. Most of the points of discussion were minor. The author then evaluated the rest of the textbooks.

#### *Additional Criteria*

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

- Space (S) used by textbooks, i.e., number of pages used for presenting Millikan's experiment.
- Schematic diagram (SD) of Millikan's apparatus.
- Brief description (BD) of the experiment.
- Examples from Millikan's (ED) data.
- Mathematical details (MD) of the experiment.

These additional criteria were based on the following: (a) the portion of space devoted to Millikan's experiment which deals with historical details, (b) comparison of textbook treatment

with respect to experimental and mathematical details, and (c) coherence of the textbook account.

### Evaluation of Chemistry Textbooks: Results and Discussion

Table 1 shows that textbooks can be divided into two main groups: those that present the Millikan oil drop experiment (22 textbooks) and those that do not deal with the experiment (9 textbooks). From the historical perspective, the latter textbooks do not follow the logical sequence of Thomson's determination of the charge to mass ratio ( $e/m$ ) of the cathode rays and the consequent need for determination of the elementary electrical charge ( $e$ ). Millikan (1947,

Table 1

*Evaluation of chemistry textbooks based on a history and philosophy of science framework (Millikan–Ehrenhaft)*

No.	Textbook	Criteria*					
		1	2	3	4	5	6
1.	Ander & Sonnessa, 1968	N	N	N	N	M	N
2.	Anderson et al., 1973	N	N	N	N	N	N
3.	Barrow, 1974	–	–	–	–	–	–
4.	Becker & Wentworth, 1977	–	–	–	–	–	–
5.	Bodner & Pardue, 1989	N	M	N	N	N	N
6.	Brady & Humiston, 1996	N	N	N	N	N	N
7.	Brescia et al., 1975	N	M	N	N	N	N
8.	Brown et al., 1997	N	N	N	N	N	N
9.	Burns, 1996	N	N	N	N	N	M
10.	Chang, 1999	N	N	N	N	N	N
11.	Daub & Seese, 1996	N	N	N	N	N	N
12.	Dickerson et al., 1984	–	–	–	–	–	–
13.	Ebbing, 1997	N	N	N	N	N	N
14.	Hein & Arena, 1997	–	–	–	–	–	–
15.	Holtzclaw et al., 1988	N	M	N	N	N	N
16.	Joesten et al., 1991	N	N	N	N	N	N
17.	Lippincott et al., 1977	N	N	N	N	N	N
18.	Mahan & Myers, 1990	N	M	N	N	M	N
19.	Masterton et al., 1985	N	N	N	N	N	N
20.	Mortimer, 1983	N	N	N	N	N	N
21.	Newell, 1977	–	–	–	–	–	–
22.	Oxtoby et al., 1994	N	M	N	N	S	N
23.	Pauling, 1977	N	N	N	N	M	N
24.	Quagliano et al., 1969	–	–	–	–	–	–
25.	Segal, 1989	N	M	N	N	S	N
26.	Sienko & Plane, 1971	N	N	N	N	N	N
27.	Sisler et al., 1980	N	N	N	N	N	N
28.	Stoker, 1990	–	–	–	–	–	–
29.	Whitten et al., 1998	N	N	N	N	M	N
30.	Wolfe, 1988	–	–	–	–	–	–
31.	Zumdahl, 1990	–	–	–	–	–	–

\*Criteria: (1) Millikan–Ehrenhaft controversy; (2) Millikan's guiding assumption; (3) suspension of disbelief; (4) Transfer of integral multiple of elementary electrical charge; (5) dependence of the elementary electrical charge on experimental variables; (6) Millikan's experiment: part of a progressive sequence of heuristic principles.

Note. S = satisfactory; M = mention; N = no mention; – = text does not deal with the subject.

cf. guiding assumptions in this article) explicitly mentioned that his determination of the elementary electrical charge was made in the context of Thomson's determination of ( $e/m$ ). Thomson (1898) himself was one of the first to devise an experiment for the determination of ( $e$ ), which formed the starting point for Millikan's own work in 1906.

### *Criterion 1*

Of the 22 textbooks that deal with Millikan's experiment, none mention (N) nor give details of the Millikan–Ehrenhaft controversy. It appears that textbooks do not appreciate the importance of controversy in scientific progress, and thus deprive students of an opportunity to see how scientists really work. By simplifying the process of scientific development, textbooks present the work of scientists as that of simply going into the laboratory and coming out with new findings and theories.

### *Criterion 2*

Six textbooks made a simple mention (M) of Millikan's guiding assumptions; following are two of the examples:

Thomson's experiments were a milestone in the search to understand the composition of the atom, but they raised two obvious questions. What is the value of the electric charge carried by the electron, and what is the electron mass? The answers were not long in coming. In 1909, the American physicist Robert Millikan and his student, H.A. Fletcher, developed an elegant experiment that yielded  $e$ , the charge of the electron. (Oxtoby, Nachtrieb, & Freeman, 1994, p. 607)

The very large value of  $e/m$  could result either from a large value of the electronic charge, or from a small value of the mass of the electron. An independent measurement of either  $e$  or  $m$  was therefore necessary, and in 1910 Robert A. Millikan determined the charge on the electron in a classic and famous experiment. (Segal, 1989, p. 412)

Sixteen textbooks made no mention (N) of Millikan's guiding assumptions; following is an example:

In 1909 Robert Millikan (1868–1953) of the University of Chicago succeeded in measuring the charge of an electron by performing an experiment known as the “Millikan oil-drop experiment.” (Brown, LeMay, & Bursten, 1997, p. 40)

It can be argued that such a presentation can easily be interpreted as an inductive generalization, viz. it was the experimental results that led Millikan to deduce the elementary electrical charge. The historical framework presented in this article shows that it was precisely Millikan's guiding assumption that helped him to understand and interpret the data.

### *Criterion 3*

None of the textbooks mentioned (N) one of the most important feature of Millikan's methodology, viz. in the face of anomalous data, a scientist perseveres with his guiding assumption, holding its falsification in abeyance—in other words, suspension of disbelief. It can be argued that general chemistry textbooks are not supposed to teach scientific research methodology. Although

it may seem surprising, this is what most textbooks do. For example, most textbooks emphasize the traditional scientific method, viz. scientists do experiments which help them to elaborate hypotheses (guiding assumptions), enunciate laws, and formulate theories. In other words, textbooks not only teach chemistry, but also inculcate research methodology. In the case of the oil drop experiment, if the traditional scientific method had been followed, Ehrenhaft's (with impeccable credentials as an experimentalist) results and not Millikan's would have been accepted by the scientific community. Of course, textbooks generally ignore controversy, and in this case Ehrenhaft's role has been conveniently forgotten. On the other hand, Millikan's contribution, if interpreted in the context of suspension of disbelief, could enrich classroom discussions.

#### *Criterion 4*

None of the textbooks made (N) the important distinction that Millikan did not measure the charge on the electron itself but rather the accretion of the electrical charge on oil droplets. Some textbooks do recognize that the charge on the droplets was an integral multiple of the elementary electrical charge (e.g., Mahan & Myers, 1990; Oxtoby et al., 1994; Segal, 1989). Nevertheless, it lacks the conceptualization that the transfer of charge between the droplets and the ionized gas occurred in integral multiples of  $e$ .

#### *Criterion 5*

Only two textbooks (Oxtoby et al., 1994; Segal, 1989) presented the experiment satisfactorily (S), by referring to the different experimental variables that made the experiment so difficult and its interpretations controversial. Some excerpts from Segal (1989) are reproduced:

Using an atomizer, microscopic spherical drops of oil are introduced into the space above two charged plates. Oil is used because it does not noticeably evaporate. . . . Gravity causes the drops to fall, but they are slowed by friction, due to the viscosity of the air. . . . The charge on the drop can be calculated from the value of its downward velocity, the magnitude of the potential difference, the known acceleration of gravity, the density of the oil, and the air viscosity. (pp. 412–413)

The reference to sphericity and evaporation of the oil drops and viscosity of the air are some highlights of this presentation. Nevertheless, such presentations do not reflect the complexity of the different variables that made the oil drop experiment so controversial.

Four textbooks made a simple mention (M) to some of the variables involved in the oil drop experiment and 16 textbooks made no mention (N). Following is an example of a textbook that made no mention (N):

A fine drop of oil drifts from the top of the apparatus through the hole into the region between the two plates. The X rays cause the drop to pick up a negative charge, and the drop is attracted toward the positive plate. At one particular voltage, the electrical and gravitational forces are balanced, and the drop remains stationary. From the charge on the plates and the mass of the drop, the charge on the drop can be calculated. (Holtzclaw & Robinson, 1988, p. 95)

Against the backdrop of the Millikan–Ehrenhaft controversy, such presentations do not tell the whole story and furthermore give the impression that to find new things, scientists need only to walk into the laboratory.

### *Criterion 6*

Only one textbook (Burns, 1996) made a brief mention (M) of the fact that before Millikan other scientists had done similar experiments, with the difference that they used water droplets which had to be abandoned as the mass of the droplet changed owing to evaporation. None of the other textbooks presented (N) Millikan's work as part of a sequence of heuristic principles, viz. study of charged clouds of water droplets by Townsend, Thomson, and Wilson, which led to the balancing of individual droplets by Millikan and Ehrenhaft and finally Millikan's oil drop experiment. Each stage in this historical process was characterized by guiding assumptions, improvement in experimental techniques, criticisms, and rebuttals. The following textbooks not only did not present the heuristic principles, but presented Millikan's contribution as a rhetoric of conclusions (cf. Schwab, 1962, p. 24): Anderson, Ford, and Kennedy, (1973); Chang (1999); Masterton, Slowinski, and Stanitski, (1985); and Sisler, Dresdner, and Mooney, (1980). All four textbooks presented the material like a message in a telegram. Following is an example:

Later in a series of experiments carried out between 1908 and 1917, R.A. Millikan found the charge of an electron to be . . . (Chang, 1999, p. 41)

Some of the other textbooks also presented the material in a manner similar to that in the above example, with the difference that they provided a schematic diagram of Millikan's apparatus and a brief description of the experiment. Such presentations lack coherence between the diagram, the description of the experiment, and the conclusions, and thus can also be considered a rhetoric of conclusions (e.g., Brown, LeMay, & Bursten, 1997; Holtzclaw & Robinson, 1988; Sienko & Plane, 1971; Whitten, Davis, & Peck, 1998).

### *Evaluation Based on Additional Criteria*

Table 2 shows that on average, textbooks devoted a space (S) of about a page to Millikan's oil drop experiment. A previous study (Niaz, 1998) showed that textbooks devote about two pages to J.J. Thomson's cathode ray experiment and about 1½ to E. Rutherford's alpha particle experiment. It is important to note that textbooks do not present Millikan's experiment in the historical context. For example, none of the textbooks referred to the work of Townsend, Thomson, and Wilson, whose work served as antecedents to Millikan's oil drop experiment. In contrast, a previous study (Niaz, 2000), based on the kinetic theory, showed that most textbooks provide some historical antecedents to the work of J.C. Maxwell by referring to Torricelli, Boyle, Charles, Gay-Lussac, Dalton, and Clausius.

Eighteen textbooks provided a schematic diagram (SD) of Millikan's oil drop experiment; of these, 16 included at least a brief description (BD) of the experiment. Only four textbooks included examples from Millikan's (or hypothetical) data (ED) and two provided mathematical details (MD). Simple mathematical details as presented in this article can easily enhance students' understanding of the underlying issues. Of the two textbooks that provided mathematical details, Ander and Sonnessa (1968, pp. 43–45) provide a fairly detailed derivation of one of Millikan's equations for calculating the charge on the oil drop. According to Matthews (1994): "Opposition to the mathematizing [in contrast to experimentation] of physics was a deeply held Aristotelian, and more generally empiricist, conviction" (p. 117).

Unless textbooks present a coherent account of the experiment based on a schematic diagram (SD), a brief description (BD), examples from data (ED), and mathematical details (MD), it will be difficult for the students to understand the significance of Millikan's contribution. One

Table 2  
*Additional evaluation of chemistry textbooks (Millikan–Ehrenhaft)*

No.	Textbook	Additional criteria*				
		S	SD	BD	ED	MD
1.	Ander & Sonnessa, 1968	3	y	y	y	y
2.	Anderson et al., 1973	1/4	n	n	n	n
3.	Barrow, 1974	–	–	–	–	–
4.	Becker & Wentworth, 1977	–	–	–	–	–
5.	Bodner & Pardue, 1989	1	y	y	n	n
6.	Brady & Humiston, 1996	1	y	y	n	n
7.	Brescia et al., 1975	1	y	n	y	n
8.	Brown et al., 1997	1	y	y	n	n
9.	Burns, 1996	1/2	y	y	n	n
10.	Chang, 1999	1/4	n	n	n	n
11.	Daub & Seese, 1996	1/4	n	n	n	n
12.	Dickerson et al., 1984	–	–	–	–	–
13.	Ebbing, 1997	1/2	y	y	n	n
14.	Hein & Arena, 1997	–	–	–	–	–
15.	Holtzclaw et al., 1988	1/2	y	y	n	n
16.	Joesten et al., 1991	1	y	y	n	n
17.	Lippincott et al., 1977	1	y	y	n	n
18.	Mahan & Myers, 1990	1	y	y	n	y
19.	Masterton et al., 1985	1	y	n	n	n
20.	Mortimer, 1983	1	y	y	n	n
21.	Newell, 1977	–	–	–	–	–
22.	Oxtoby et al., 1994	2	y	y	y	n
23.	Pauling, 1977	1 1/2	y	y	y	n
24.	Quagliano et al., 1969	–	–	–	–	–
25.	Segal, 1989	1 1/2	y	y	n	n
26.	Sienko & Plane, 1971	1	y	y	n	n
27.	Sisler et al., 1980	1/4	n	n	n	n
28.	Stoker, 1990	–	–	–	–	–
29.	Whitten et al., 1998	1	y	y	n	n
30.	Wolfe, 1988	–	–	–	–	–
31.	Zumdahl, 1990	–	–	–	–	–

\*Criteria: S = space (no. of pages) used by textbooks; SD = schematic diagram of Millikan's apparatus; BD = brief description of the experiment; ED = examples from Millikan's data; MD = mathematical details of the experiment; y = yes; n = no; – = text does not deal with the subject.

of the textbooks (Segal, 1989, p. 441) included the following end of chapter question, which can help improve coherence:

Which of the following statements about Millikan's oil drop experiment is TRUE?

- When the electric field is turned on, all the oil drops move toward the positively charged plate.
- The charge on each oil drop is the electronic charge.
- In the absence of the electric field, the speed with which the drop falls depends only upon the acceleration of gravity.
- Oil drops, rather than water drops, were used because oil is easier to see.
- Some oil drops become positively charged and some negatively charged after colliding with gaseous ions.

At this stage, it is interesting to mention that one of the textbooks (Oxtoby et al., 1994, pp. A-2, A-3) presented 13 values of experimental determinations of  $e$  that varied from 4.894 to  $4.941 \times 10^{10}$  esu, reproduced from Millikan (1911). These values are used to explain the difference between precision and random errors. Authors point out that none of the 13 values of  $e$  are far from the rest, and hence all can be used to calculate the average and the standard deviation. However, this ignores the fact that Millikan discarded values of  $e$  that were far from the expected value. It is suggested that textbooks could use such opportunities to illustrate the role of guiding assumptions and suspension of disbelief.

Another textbook (Brescia, Arents, Meislich, & Turk, 1975, pp. 156–157) presented the data in Table 3 from one of Millikan's experiments. Based on these data, the following questions were asked: (a) What is the elementary electrical charge? (b) Calculate the charge on each drop in units of the elementary electrical charge. (c) Is the elementary electrical charge calculated independently of the suppositions with respect to the nature of electricity? (d) What should be the charge on the drop, to change the value of the elementary electrical charge? It appears that the Millikan–Ehrenhaft controversy lurks throughout this problem. Nevertheless, the authors did not mention it, and this was the nearest that any textbook came in alluding to the controversy.

This study included undergraduate general chemistry textbooks published over a fairly broad period (1968–1999). It appears that with respect to the Millikan oil drop experiment, textbooks have not changed much over this time.

### Conclusions

Most textbooks do not present Millikan's oil drop experiment within a historical, much less philosophy of science framework. None of the textbooks mentioned the problematic nature of the experiment and the controversy that ensued between Millikan and Ehrenhaft. According to Silverman (1992):

... science instruction that ignores the element of controversy in science gives an erroneous impression of how scientists actually work—a sterile impression not likely to fire the imagination and foster the curiosity of students . . . (p. 164)

For most textbooks, Millikan walked into the laboratory and came out with extraordinary experimental results which provided support for the elementary electrical charge. The presentation of some textbooks can be construed as a telegram message or what Schwab (1962) referred to as a “rhetoric of conclusions.” Most textbooks lack coherence among Millikan's guiding assumption, schematic diagram of the apparatus, description of the experiment, and mathematical details. This study has important implications for general chemistry textbooks, and it is sug-

Table 3

Oil drop	Mean charge on drop (C)
1	$16.0 \times 10^{-19}$
2	$1.60 \times 10^{-19}$
3	$9.55 \times 10^{-19}$
4	$1.59 \times 10^{-19}$
5	$19.2 \times 10^{-19}$



gested that by emphasizing the following history and philosophy of science aspects, classroom discussions can be enriched:

1. If the traditional scientific method (as presented by most textbooks) had been followed, the scientific community would have accepted Ehrenhaft's experimental findings. Textbooks can highlight the difference between the methodologies of Millikan and Ehrenhaft to illustrate how the progress of science is characterized by competition among rival interpretations.
2. A brief mention of the Millikan–Ehrenhaft controversy can open a new window for students with respect to how two well-trained scientists can interpret the same set of data in two different ways.
3. Millikan's perseverance with his guiding assumptions shows how scientists can overcome difficulties with anomalous data.
4. Millikan's methodology is a good illustration of what modern philosophers of science consider to be important characteristics of scientific progress, viz. role of falsification, confirmation, and suspension of disbelief.
5. Because of the incidence of a series of experimental variables, Millikan's classic oil drop experiment is difficult to perform even today.
6. Millikan's major contribution consists of discovering the experiment to provide confirmation for the elementary electrical charge.

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