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Science education for democratic citizenship through the use of the history of science

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Abstract Scholars have argued that the history of science might facilitate an understanding of processes of science. Focusing on science education for citizenship and active involvement in debates on socioscientific issues, one might argue that today's post-academic science differs from academic science in the past, making the history of academic science irrelevant. However, this article argues that, under certain conditions, cases from the history of science should be included in science curricula for democratic participation. One condition is that the concept of processes is broadened to include science–society interactions in a politically sensitive sense. The scope of possibilities of using historical case studies to prepare for citizenship is illustrated by the use of a well-known case from the history of science: Millikan's and Ehrenhaft's ''Battle over the electron''.

Keywords Science education for citizenship · Socioscientific issues · History of science · Nature of science · Post-academic science · Science curriculum

1 Introduction

Many science educators have suggested using the history of science as a context for students' learning about the nature of science (NOS) (Irwin 2000; Klopfer 1969; Matthews 1994; Monk and Osborne 1997). My intent here is to discuss what role the history of science might play in a science curriculum aiming at empowering lay people to deal fruitfully with societal issues with a science dimension. Several science educators have pointed to the inclusion of the history of science in science teaching as a motivating factor and source of variation (Holton 1995; Millar and Osborne 1998; Shamos 1995). The inclusion of human actors with hopes, struggles and success probably have a motivating

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effect on many learners. In 1969, Klopfer (1969) stated that the history of science has the potential of contributing to insight into the *procedural*, the *contextual*, and the *conceptual* aspects of science. Concerning science for democratic citizenship, I will argue that the inclusion of the history of science provides possibilities in relation to *procedural* and *contextual* aspects. Firstly, it makes it possible to teach aspects of NOS in contexts that might provide illustrations, depth and understanding. Secondly, it provides ‘‘full-scale’’ illustrations of science–society interactions. Although care need to be taken not to base conclusions on one single example, I will use Millikan’s and Ehrenhaft’s battle over the electron to exemplify and examine these possibilities. The separation of procedural and contextual aspects of science certainly has some limitations. However, it makes it possible to visualize how the former active segregation of science from its social context has been giving way to a mode of scientific research involving active science–society integration (Gibbons et al. 1994). Klopfer (1969) also stated the possibility of increased insight into the scientific *concepts* involved in narratives from the history of science. While content knowledge is relevant for understanding issues with a science dimension, the focus in this article is nevertheless delimited to learning about NOS and science–society interactions.

Science education for citizenship refers to science education aiming at preparing students for active, informed, critical and responsible participation in situations where insights into different aspects of science might improve the quality of students’ participation (Kolsto 2001a). One of the main arguments for science education for citizenship is the argument from democracy (Driver et al. 1996; Millar 1996). The argument emphasizes the role of science in society. One characteristic of our society is the personal, social and political issues related to environmental problems or to risks to human health. Topical examples are environmental considerations when shopping and the use of irradiated food and gene modified organisms. These issues have a science dimension and are often denoted as socioscientific issues (Sadler 2004). Millar et al. (1998) state that ‘‘[f]or most people, their contact with science is the many socio-scientific issues that confront them both as individuals and as members of society’’ (p. 19). This situation is the reason for why this article on science education for citizenship focuses on democratic participation in debates on socioscientific issues. In general, the purpose of citizenship education, according to Waghid (2005), is to prepare students for informed participation in public dialogue about questions of justice and morality. Consequently, science education for citizenship focusing on socioscientific issues need in general to include aspects of democracy education and moral education in addition to insight into different aspects of science. Democracy education, including the development of moral character, comprises acquisition of disciplinary insights in addition to affective and behavioral dimensions (Berkowitz and Simmons 2003). Therefore, a science curriculum for citizenship ideally includes, among other issues, practicing democracy; fostering a psychological foundation for democratic participation; and developing general moral character. Important elements of moral education like opportunities for students to practice good character and to reflect on moral issues (Berkowitz and Simmons 2003) seems especially suitable, when including socioscientific issues in the classroom. However, this article is about the potential use of narratives from the history of science for developing insights into NOS and science–society interactions, as prerequisites for knowledge-based examination of and argumentation in socioscientific issues. Thus, the focus is on insights about science, and not on learning about democracy or affective and behavioral dimensions of science for citizenship education.

Nevertheless, narratives from the history of science do involve moral aspects, as human activity normally does. The moral aspects may vary, from the need for honesty and the disclosure of funding agents and assumptions, to the role of epistemic and non-epistemic values in scientific research. Although questions about values and morality will be touched upon, I will emphasis the possibility of using the history of science in developing a knowledge base for examination of and argumentation in socioscientific issues. Hence, the phrases science for citizenship and science for democratic participation will be used interchangeably.

The science inherent in such issues often involves controversy and expert disagreement. As an example, researchers are at present debating whether magnetic fields from power transmission lines might increase the risk for childhood leukemia (Ahlbom and Feychting 2003). Several educational organizations and science educators have argued that insight into NOS needs to be included in science curricula for citizenship (AAAS 1989; Driver et al. 1996; Millar and Osborne 1998; NRC 1996; OECD 2001). In particular, knowledge of NOS has been judged relevant for the examination of socioscientific issues (Abd-El-Khalick 2003; Kolstø 2001a; Millar and Wynne 1988; Ryder 2001). However, as Abd-El-Khalick (2003) reminds us, students' wanting insight into NOS represents a challenge we have to face:

> Unfortunately, a long-standing line of research into pre-college students' views of NOS indicates that the greater majority of students still harbour the sort of naïve views of science [...] that would hinder engagement in critical discourse regarding socioscientific issues. (Abd-El-Khalick 2003, p. 46)

Discussing reported statements of non-scientists in the media following the Chernobyl accident, Millar and Wynne (1988) concludes that

> there is at least as great a need for wider public understanding of the internal processes by which scientific knowledge is generated and validated as of the contents of specific areas of science. (Millar and Wynne 1988, p. 395)

There are also indications that students get confused when confronted with expert disagreement and ask whether this might be due to vested interests or incompetence (Kolstø 2001b). A premise for my discussion is therefore that insight into NOS and science–society interactions is important when participating in democratic debates on socioscientific issues. However, this implies that a discussion on how historical narratives of science can illustrate various characteristics of science need to be based on an analysis of what characterizes the science involved in topical socioscientific issues.

1.1 Science involved in socioscientific issues

School science typically emphasizes consensual scientific knowledge. However, the science involved in socioscientific issues is often non-consensual frontier science. The history of science is the history of frontier science as it includes the processes through which scientific knowledge is produced. The use of historical case studies therefore represents an opportunity for students to gain deeper insight into the nature of science in the making. However, science curricula for democratic participation ought to relate to the science people encounter in today's society, and the relevance of historical cases for learning about current science cannot be taken for granted.

On the contrary, the inclusion of the history of science in science curricula for democratic participation has to take into account that, during the twentieth century, some of the characteristics of science changed. Following the success of government initiated scientific research during the Second World War, with the nuclear bomb and the radar as cases in point, the conception of science as a handmaiden to solve society-related problems emerged (Ravetz 1995). Aikenhead (1994) claims that science has been undergoing a process of ''socialization'' whereby ''[g]overnment, industry, and the military have become the dominant patrons of scientific activity'' (p. 16).

Several authors have claimed that these changes have resulted in new modes of scientific knowledge production. Conceptualizations of new modes of sciences includes *post-normal science* (Funtowicz and Ravetz 1993), *mode 2* (Gibbons et al. 1994) and *the triple helix* (Eztkowitz and Leydesdorff 1997). I will base my discussion on Ziman's (2000) account of the observed changes in science. He sets out to describe both traditional and new modes of scientific research. He also wants to provide an account that mediates between traditional and radical understandings of the impact of social dimensions on scientific research. These two aims make his account a good starting point for discussing possible consequences for science education: it is probably accessible for science teachers (including those who at the outset hold a more positivistic view of science), and it explicitly discusses the reliability of scientific knowledge. In addition, his account is explanatory for understanding the role of science and scientists in socioscientific issues.

Ziman (2000) differs between industrial, academic and post-academic modes of scientific research. In industrial research, scientists' primary goal and duty is to solve problems with an assumed utility for industrial technological needs (Ziman 2000). This focus on utility contrasts traditional university based science, which is undertaken to develop the discipline further without any particular application in view. In this traditional mode of scientific research, which Ziman (2000) labels *academic science*, the fundamental credo is that the pursuit of knowledge is of value in itself. However, scientists' research instruments have become increasingly expensive without a corresponding rise in universities' general funding, and research projects are characterized by increasing complexity and collaboration among specialists. Consequently, research has become more expensive, and the writing of research proposal has become an important activity for university-based scientists. Simultaneously, the patrons of science, whether these are commercial firms, governments, military or private organizations, increasingly ask what they receive in return. The result is that the norm of *utility* has diffused into the research culture.

According to Ziman (2000), this change in goals has lead to the emergence of a new mode of scientific research, which he labels *post-academic science*. In Ziman's (2000) conception, post-academic science represents a structural convergence between the academic and the industrial modes of research. Another important characteristic of post-academic science is the entrance of non-epistemic values through its focus on utility. Utility is a concept with a moral dimension as it cannot be determined without reference to human goals and values. Ziman (2000) concludes, that in general ''[p]ost-academic science, being much more directly connected into society at large, has to share its larger values and concerns'' (p. 74).

Furthermore, in the post-academic mode of research, the scientists' autonomy is reduced. Although the researchers might have autonomy on the more detailed level, the problem area to be studied is typically defined by the funding agency. Thus, the typical post-academic scientist has become a contractor and has to make dispositions that might give him research contracts. Such research funding relationships makes it hard to claim full objectivity and disinterestedness. Jenkins (1992) asserts that science' integration with industry and technology makes the older pictures of science as ''the disinterested pursuit of objective truth'' (p. 232) untenable.

Finally, post-academic scientists often work under contracts that prevent them from disclosing all their results immediately. This practice is at odds with the important norm of communalism in academic science and weakens the role of argumentation and criticism in science. The reliability of findings is thus more uncertain, and, as in the case of research on tobacco and cancer, a funding company might even prevent the publication if funded research gives discomforting results.

To sum up, post-academic science is characterized by a focus on *utility* as defined by the patrons of science, the scientists' need to achieve *funding*, and the presence of vested *interests*. In consequence, the *science–society interactions* are more complex in post-academic science than in traditional academic science.

Socioscientific issues are characterized by the presence of actors with diverging interests. Consequently, the presence of post-academic science with links to vested interest makes insight into the science–society interactions involved in this mode of scientific research paramount. It also induces the question of whether stories from the history of science, understood as the history of academic science, have anything to offer in a science curriculum for citizenship. In this article, I will argue that historical narratives in science have a potential relevance for a science curriculum for citizenship, based on three interrelated reasons. First, different modes of scientific research today *coexist*. Secondly, *similarities* between the different modes of science exist and define aspects of science where historical narratives can foster *comprehension*. Thirdly, the learning of aspects of different modes of science in their *historical order* is sometimes pedagogically advantageous. In addition, the inclusion of both modes of science makes *comparison* between different modes of science possible.

The differences between academic and post-academic modes of research make it necessary also to focus on possible *pitfalls*. The image of science conveyed might be misleading if only cases from academic science are used, or if the narratives do not involve enough depth and details. If science–society interactions are not included, the misconception of the separation of science from the rest of society might be reinforced. Finally, if used to illustrate ''undisputable facts'' about NOS, the implicit epistemology communicated might prevent an appreciation of the role of argumentation and criticism in science.

Consequently, in addition to exemplifying possibilities of using historical narratives in a science curriculum for citizenship, I will argue for the importance of considering carefully certain issues regarding what cases and accounts to use, including their possible limitations. To illustrate different points I want to make about what narratives from the history of science might provide, I will present one specific story that has fascinated me personally: the quest for the nature of electric charge. The story is better known as Millikan's oil drop experiment or the ''Battle over the electron''. Importantly, the idea of illustrations is not only a pedagogical luxury but is crucial for students' development of engagement and deeper understanding. The case story will therefore be used for two purposes: first, to discuss and exemplify the scope of possibilities in relation to important objectives in science curricula for citizenship, secondly, to illustrate how a closer look at a specific case can provide the concretizations and convincing details necessary to develop understanding.

2 Millikan's oil drop experiment

At the beginning of the twentieth century, physicists were still in doubt whether there existed a minimum quantum of electric charge, carried by a particle called *electron*. The American physicist Robert Andrews Millikan decided in 1908 to investigate the problem. He set up an experiment where he injected small charged droplets of oil into a vertical electric field between two parallel metal plates (see Fig. 1). The idea was that the

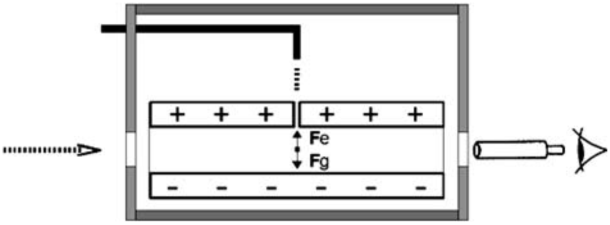

Fig. 1 The drawing shows a sketch of the main features of Millikan's apparatus based on his drawing of the experimental setup in Millikan (1913). Oil drops are produced by a spraying apparatus. A small oil drop enters the space between two charged plates through a small whole in the upper plate. Droplets become charged by friction with each other during the spraying process and through the use of Röntgen rays from the left. When the gravitational force Fg and the electric force Fe acting on the charged oil drop are of equal strength, the oil drop is suspended. Through a small window Millikan could see the oil drop and its movements

gravitational force would influence an oil drop to fall downwards, while the electric field would influence a droplet to move upwards due to their charge.

By adjusting the strength of the electric field, Millikan could make droplets of oil rise slowly in the space between the two metal plates. He then measured the speed with which they rose and observed the voltage used. From these data he could calculate the charge of the oil drop. Each time he performed an experiment on an oil drop, he found the charge on the droplets to have the anticipated value of the charge of the electron multiplied by an integer. Through his oil drop experiment Millikan thus managed to identify the electric charge carried by the electron.

This version of the story is rather short and superficial. However, it is probably typical of the accounts of the story told in science textbooks (Niaz and Rodríguez 2005; Knain 2001). It emphasizes the role of the single scientist discovering the laws of nature in his laboratory through a well-designed experiment. The process of discovery is implicitly portrayed as uncomplicated and based on one experiment and one man's work, and no non-epistemic personal or social values are involved. However, there are also other versions of this narrative. Drawing upon Millikan's (1951) autobiography and Holton's (1978) thorough study of the case, I will now give another account of the story; one that is more detailed and perhaps contains thought provoking elements.

2.1 The ''battle over the electron''

Is electric charge quantified or continuous? And does a particle carrying a negative electric charge exist? Already in ancient Greece, the natural philosopher Democritus proclaimed that matter was composed of indestructible particles. Does an electrically charged particle, an electron, exist, which is indestructible and part of ordinary matter? The physicist Joseph John Thomson had suggested the existence of a particle carrying a small negative electric charge, but the existence of the particle was in dispute. In 1908 Millikan started to work on the problem.

In Europe at that time there were many physicists, among them Ernst Mach, who wanted a science free from ''unnecessary'' metaphysical hypotheses such as atomism (Holton 1978; Matthews 1994). Continuity was preferred for philosophical reasons (Bernal 1978). Mach rejected the existence of unobservable objects and claimed that science should only deal with entities that could be experienced and observed by empirical means

(Matthews 1994). Another of these European physicists was an accomplished young man named Felix Ehrenhaft, associate professor at the University of Vienna. He was also experimenting to reveal the nature of charge.

At this time, Millikan was still a rather unknown American physicist at the University of Chicago. He was eleven years older then Ehrenhaft, and had produced few scientific publications. His philosophy was not as sophisticated as that of Ehrenhaft. Millikan confessed to a pragmatic, straightforward emphasis on ''concrete visualizations'' (Holton 1978, p. 36). When Millikan decided to work on the charge of the electron, he was well aware that the existence of the electric charge quantum was regarded as a fundamental question in physics at that time.

In his first method, which Millikan took over from Charles T. R. Wilson, he did not look at single oil drops, but on the falling of the top layer of a whole *cloud* of charged *water* droplets. Using this method Millikan and his student Louis Begeman found a value for the electric charge of the electron somewhat below the expected and with a high spread in the measurements. High spreads could be seen to indicate that charges of all different sizes existed and not only integral values of a minimum quantum. Millikan was criticized for the way he produced the cloud of droplets and started to improve the apparatus he used. Among the improvements he made was the use of higher voltage to produce a stronger electric field. But when he switched on the new field for the first time, something happened. The cloud in his apparatus just dissipated, instantaneously and completely (Holton 1978).

At first he thought the experiment was ruined, but, looking through the inspection window in the apparatus, he observed that a few individual droplets remained in view. He suddenly realized that he had made a break-through! The existence of remaining droplets could enable him to carry out measurements on *individual* droplets with a charge due to only one or a few individual electrons! In his own words: ''[seeing the droplet] moving upward with the smallest speed that it could take on, I could be certain that just one isolated electron was sitting on its back'' (Millikan 1951, p. 99).

However, he soon observed a new strange phenomenon. Sometimes charged water droplets floating in the electric field suddenly changed their motion radically. The discontinuity of this observation was interesting. In fact it fitted well with the hypothesized discontinuity in the concept of quantified charge. Again in Millikan's own words: ''I had seen a balanced drop suddenly catch an ion [from the surrounding air]'' (cited in Holton 1978, p. 38).

The value Millikan found for the electric minimum charge was very close to the anticipated value. In a paper where he published these results, Millikan also gave an account of how he judged his different measurements. ''The observations marked with a triple star are those which were marked 'best' in my notebook....'' And also: ''Second, I have discarded three observations which I took on unbalanced drops'' (cited in Holton 1978, p. 53) (because he judged them to be uncertain). Holton (1978) comments on these judgments in the following way: ''Millikan was evidently saying that he knew a good run when he saw one.'' (p. 53).

In his paper Millikan was critical to the accuracy of results published by Ehrenhaft, even if Ehrenhaft's method and results at the time were rather similar to his own. (Millikan argued for instance that Ehrenhaft's method made it necessary to carry out two sets of measurements on each charged particle, with and without the electric field present, thus increasing the uncertainties.) Millikan's dismissal of Ehrenhaft's work soon received an answer. In Ehrenhaft's next article, he recalculated the charge on each drop reported in Millikan's paper. Instead of using the average of measured voltages as Millikan had done, he calculated the charge for each single droplet. The result was a large spread of values of the charge on the drops. This result weakened the claim for the existence of a minimum charge.

Ehrenhaft's own experimental results, which he reported in the same paper, were remarkable. Ehrenhaft found droplets of liquid, metal particles and other small objects to have charges of half, a fifth, a tenth, a hundredth, and even a thousandth of that of the electron. He concluded that indivisible quantities of electric charge did not exist at the level found by Millikan.

Meanwhile Millikan had continued to improve his method. With this improved method Millikan, together with his assistant Harvey Fletcher, could publish new and very accurate results. They reported to have ''found in every case the original charge on the drop [to be] an exact multiple of the smallest charge which we found that the drop caught from the air'' (Millikan 1911, p. 360). Again he frankly explains that some measurements had been excluded because they yielded values of the electric minimum quantum too low compared to their other findings.

In retrospect we all know that in the end, Millikan's results were judged as convincing by other physicists, while Ehrenhaft's were not. Perhaps surprisingly, Holton (1978) concludes that physicists discussing Ehrenhaft's experiments were not able to suggest errors in his method. His results nevertheless seem to have been wrong. One important difference between their methods though, was their use of data. Holton argues that the problem seemed to be that Ehrenhaft and his colleagues used all their collected readings: good, bad, and indifferent.

In his third major paper Millikan announced that the uncertainty in his value of the elementary charge, according to his new measurements, was 0.03 per cent. This was indeed a very accurate result. However, Millikan's notebooks from the experiments have been found, and from these it is clear that he also this time had made judgments as to the quality of the different runs. He often wrote down evaluations like ''battery voltage dropped'', ''stopwatch error occurs'' and ''the distance must be kept more constant'' (cited in Holton 1978, p. 69). On one occasion he wrote ''*e* [calculated elementary charge] = 4.98 which means that this could not have been an oil drop'' (cited in Holton 1978, p. 69) (it could for instance have been dust in the chamber). He comments on the different runs by writing e.g.: ''Error high will not use''; ''Very low Something wrong''; ''Exactly right''; ''Publish this Beautiful one''; ''Beauty. Publish this surely, beautiful!'' (cited in Holton 1978, pp. 67–71).

In Ehrenhaft's view it is Millikan's strongly held assumption of electric charge to be ''atomized'' which forces him to assume further, without proof, a high level of ''error'' sometimes to be present. In Millikan's view Ehrenhaft's way of using data ''would force one to turn one's back on a basic fact of nature - the integral character of *e* [the charge of the electron]'' (Holton 1978, p. 69).

This account of the story illustrates how researchers' theoretical assumptions influence their work as scientists. Moreover, it illustrates the complex interaction between theory and data. Both Millikan and Ehrenhaft struggled to produce accurate measurements, but with different guiding hypotheses. Based on his empirist view, Ehrenhaft seems to have accepted all measurements obtained. Based on his belief in the existence of unobservable electrons, a realist view of scientific knowledge, Millikan was lead to look for errors and uncertainties and adjust methods instead of judging his hypothesis as falsified.

The story also shows how Millikan and Ehrenhaft published their results and received criticism from colleagues and each other. This criticism obviously stimulated Millikan to improve his methods and refine his argumentation. In the end Millikan's results where accepted by the scientific community as reliable, while Ehrenhaft's results sank into oblivion although errors were never identified.

Obviously, the battle over the electron was academic science. In Millikan's final paper on the issue no interested parties outside the research community are acknowledged, while this is customary in post-academic science (Ziman 2000). Only two research assistants are mentioned.

Millikan's results constituted an important step forward towards establishing the unitary nature of electric charge. In 1924 he received the Nobel price in physics, partly for his work on the charge of the electron.

3 The nature of science

I will now turn to exploring what possibilities narratives like the ''Battle over the electron'' might provide for the teaching and learning of NOS. A range of tenets about science have been suggested for inclusion in school science (Driver et al. 1996; Osborne et al. 2003), indicating that a selection has to be made. Reoccurring issues in students' and lay people's dealing with socioscientific issues are diverging measurements and research findings, expert disagreement and uncertainty (Irwin 1995; Kolstø 2001b; Ryder 2001). As these issues involve scientific knowledge or knowledge claims published, it is important to include topics related to social aspects of science (e.g. peer review, publication, argumentation, criticism, consensus formation). In addition, when introducing NOS as a curriculum component, we have to be aware that insights brought about by science studies do not represent new ''facts'' about science. The new insights represent hypotheses and issues to reflect upon. This is also important for pedagogical reasons, in order for the epistemology implicitly communicated not to conflict with the epistemology explicitly expressed. Based on these considerations and the more thorough discussions of topics of relevance for dealing with socioscientific issues in Abd-El-Khalick (2003), Kolstø (2001a) and Ryder (2001), I believe the following interrelated learning tenets related to NOS to be of relevance for democratic citizenship:

1. Scientific concepts are constructed by humans.
2. Observations and theories are mutually dependent.
3. Measurements and results always involve uncertainties.
4. Argumentation is an important part of science.

What might the history of science have to offer in relation to these learning tenets, and what is their relevance for a science curriculum for democratic participation? Concerning the first tenet, I believe the Battle over the electron showed that the idea that charge is atomized, i.e. composed of indivisible elements, was not induced from the experimental data. On the contrary, Millikan had this idea when he started out his experiments, and the idea could be traced back to ancient Greece. We also saw that other researchers held a different view. The battle over the electron therefore illustrates that scientific theories are not created through induction from empirical observations but are invented by humans before nature's response to the theory is explored. But the Millikan story might also be used to illustrate that some ideas, or hypotheses, are better than others when we are trying to describe nature.

It also seemed that Millikan had to hold on to his idea persistently, over a long period of time, to be able to gain convincing results. Similarly, Ehrenhaft kept strongly to *his* hypothesis, and interpreted *his* findings to be in accordance with *his* idea of continuity.

Consequently, the idea that a hypothesis has to be rejected as soon as observations do not fit with the theory, is not supported (Matthews 1994). On the contrary, Millikan inspected possible sources of errors instead. Neither did Ehrenhaft regard Millikan's observations as a falsification of his own theory. The simplified version of Popperian falsificationism called naïve falsificationism is nevertheless found in science textbooks (Matthews 1994).

The idea that scientific concepts are constructed by humans implies that scientific conceptions might in principle change, due to new ideas and further insight. There is an important consequence of this idea concerning lay people's ability to engage in debates on socioscientific issues. A widespread myth about science is that scientific knowledge is true in an absolute sense (Aikenhead 1987; Bauer 1994; Irwin 2000). To change the conception that science deals with *facts* is of paramount importance for democratic debate, as the idea of scientific *facts* implies that lay people have ''no right to doubt'' (Bauer 1994, p. 63). Historical studies can be used to show that scientific claims always hinge on evaluation of different evidence, and that this evaluation is done through argumentation and criticism both in the ''laboratories'' and within the wider scientific community. Insight into the constructed, and thus fallible, provisional and debatable nature of scientific concepts is important for active citizenship as it empowers citizens to scrutinize and to debate scientific claims.

Concerning the second tenet, stating that observations and theories are mutually dependent, the Battle over the electron illustrates two important issues. Firstly, that theory guides the *collection* of data. Theory guides the design of the experiment and the researcher's decisions about what observations to look for. Secondly, it illustrates that the *interpretation* of collected data is also guided by theory. Millikan seems to have evaluated oil drop observations which did not fit into his hypothesis more critically than cases where calculated charge on the electron was close to the anticipated one. Through this critical evaluation he was able to detect a range of possible sources of errors which could explain the deviations from the anticipated values. And obviously his interpretations and calculations were guided by his theoretical understanding of the different parts of the apparatus used, e.g. the interactions between a charged oil drop and the gravitational field, the electric field, the surrounding air and the Röntgen rays used to ionize the oil drop. In addition, we also saw that observations, in the end, *had* an impact on the final acceptance of one, and only one, of the theories. Thus examples from the history of science might be used to illustrate the complex interplay between theory and observations.

The important idea of the *theory-ladeness* of observation easily leads to problems in understanding how observations influence theories. An emphasis on *observations* as a means to build new knowledge about nature easily leads to difficulties in understanding the constructed character of scientific concepts and theories. The use of actual cases from the history of science might provide contexts and details that make it easier for the learner to understand some of the complexity of the interplay and not only to jump to extreme epistemologies giving primacy to theory over observations or vice versa. Clough (2006) suggests that we try to convey to our students that ''data is not telling the scientists what to think. Instead, scientists have to develop ideas that will account for the data'' (p. 478). This focus, he states, provides opportunities to ask thought-stimulating questions like ''[h]ow does the need to make sense of data account for disagreements among scientists and the inventive character of science?'' (p. 478).

The presence of expert disagreement in the battle over the electron exemplifies how the history of science can illustrate insights of relevance for science for citizenship today. Instead of interpreting expert disagreement solely in terms of vested interests, citizens can understand that science involve professional judgment based on theoretical concepts, observations and epistemic (and non-epistemic) values. If expert disagreement is considered legitimate, citizens engaged in an issue can consider antagonist experts' mutual criticism with respect, and use such criticism to identify underlying values and weak aspects in the arguments involved.

My third learning tenet was that measurements and results always involve uncertainties. In a metastudy of case studies on lay people in interaction with science-related issues, Ryder (2001) reports that interpretation of measurements and uncertainties emerged as important issues. In the study by Millar and Wynne (1988) on information in media following the Chernobyl accident, they describe how small daily changes in measurements of radioactivity in milk were presented as real changes. They argue that the way science-based figures were used could develop an already widely held lay impression that science and scientific measurements are necessarily precise and accurate. The view of science as precise and accurate is in stark contrast for instance to the changing predictions and advice given by scientific experts to Cumbrian sheep farmers in the aftermath of the Chernobyl accident (Wynne 1996).

Examples from the history of science, like Millikan's fight to reduce the uncertainties in his measurements, might here be used to explore the characteristics of scientific measurements and knowledge claims. In the Millikan story, it is obvious that uncertainties were one of his main concerns. Looking at his papers on the issue, we can see that a substantial number of pages are devoted to discussions of what he did to minimize uncertainties. In his 1911 paper, for instance, he explains how he took down and reassembled the apparatus several times to avoid systematic errors in the measurements. Inspection also shows that measurements and calculated values for the charge of the electron are given with quantitative information of estimated errors. Going further back, we can find that Wilson and his predecessors also had performed experiments making them able to calculate the charge of the anticipated electron. However, the uncertainties in their results were too great to make their results convincing. The importance of focusing on uncertainties and sources of errors is therefore well illustrated in the case of the Battle over the electron.

For citizens engaged in a socioscientific issue, awareness of uncertainty in science might prevent them for putting too much trust in individual measurements, and from interpreting diverging observations only in terms of stakes and incompetence.

The fourth tenet states that argumentation is an important part of science. The Millikan story involved a lively debate within the community of physicists both on the philosophical aspects of the different theories, and on Millikan's and Ehrenhaft's methodologies and experimental findings. The necessity to convince his colleagues stimulated Millikan continuously to improve his apparatus and methodology. In order to convince colleagues both Millikan and Ehrenhaft had to publish their results. The focus on publication illustrates that scientific knowledge is historically defined as public knowledge (Ziman 2000). However, the application of the norm of communalism in post-academic science is an area of controversy, and is thus one of the challenges related to educational use of the history of science.

Nevertheless, the different results of Millikan and Ehrenhaft forced the scientific community to argue and debate the adequacy of the different theories, methodologies, interpretations and results. Also in their papers, Millikan and Ehrenhaft put forward criticism of each other's methods and results. The Millikan story therefore indicates that narratives from the history of science might be used to illustrate the important role argumentation and criticism play in scientific knowledge production. It was not Millikan or Ehrenhaft who decided that Millikan's knowledge claim was correct, but the scientific community they were part of.

Insight into the important role of disagreement and argumentation might make it easier for non-scientists to appreciate the emphasis of publication in science. Thus, students can realize that findings published in peer reviewed journals in general are more reliable then claims put forward in the grey literature, secret reports and oral communication. In general, students might come to appreciate how consensual science is more reliable than claims from the frontiers of science. This insight might also increase lay people's acceptance of science as not being able to provide answers in a short time, and thus provide the insight that decisions on socioscientific issues must sometimes be based on other arguments than the science-based one (Collingridge and Reeve 1986).

3.1 Relevance for understanding post-academic science

If the science involved in current socioscientific issues is post-academic, what will then be the relevance of the insights described above? In the introduction, it was stated that post-academic science deviated from academic science in its focus on utility and the presence of stronger science–society interactions. However, also post-academic scientists want to publish in peer reviewed scientific journals. Science–society interactions are more pronounced in post-academic science then in academic science. Nevertheless, aspects of academic science that are less related to such interactions, e.g. procedural aspects, might be present also in post-academic science. If that is the case, insights from narratives from academic science will still have relevance for understanding science involved in socioscientific issues. Looking at the four tenets above, the three first obviously also hold for post-academic science. Scientific concepts made using post-academic modes of research are also constructed by humans. The description of observations and theories as mutually dependent also holds for post-academic science. Moreover, not even post-academic scientists, with all their advanced instruments, can avoid uncertainties. In fact, scientists believe uncertainty to be a basic aspect of man's interaction with nature.

From a pedagogical point of view, characteristics common to both modes of science might be easier for students to comprehend using narratives from academic science. Narratives of post-academic science will in general be more complex and typically involve more people, more actors, more money and more advanced science and equipment. With limited time and effort, narratives of academic science will normally have a better chance of becoming transparent to the learner, and thus provide insights. This, of course, implies that the developers of curricula material need to be aware of the existence of the two modes of science (in addition to other modes of scientific practice, like industrial research and professional consultancy). Based on this awareness they can focus on aspects relevant to both modes.

Whether the fourth tenet is relevant for describing both modes of research requires a more complex answer. Argumentation presupposes openness. This virtue might interact with the ''virtue'' of utility, and thus involves the kind of science–society interactions that I will discuss in the next section.

4 Science–society interactions

So far, I have discussed how narratives might illustrate insights into the process of research, but without taking into account science–society interactions involved in scientific research. The inclusion of such interactions has been an aim for several science education reforms and curriculum initiatives over the last decades (DeBoer 1991; Solomon and Aikenhead 1994; Ziman 1980). Science–society interactions concern the mutual dependency of science and society and connections through which resources, information, competence and knowledge are exchanged. In addition, it concerns questions related to the impact of scientific knowledge and research upon the rest of society and the effect cultural, societal and political situations might have on scientific research and discoveries. Should for instance scientists decide what energy types a country should carry out research on? Do the surrounding culture and scientists' personal philosophies influence the content or presentation of their discoveries? How might scientific research relate to specific interests and power? Such questions, while related to the process of scientific knowledge production, also relate to political and institutional aspects of science. Such mutual influences between science and the rest of society might be illustrated by the use of historical case studies. Science–society interactions concern abstract topics, making the use of illustrations paramount. Historical case studies have at least two advantages in this respect: Firstly, they represent ''ended stories'', making it possible to study all aspects of such interactions. Secondly, their political sensitivity has usually diminished, making them easier to analyze from a diversity of perspectives and easier to include in a science curriculum.

However, the use of historical cases of academic science will in general involve science–society interactions that differ from interactions involved in post-academic science often relevant in socioscientific issues. As this is a huge area, and as science is focused upon in this article, I will mainly discuss how society at large might influence scientists and scientific research. Through resources and ideas, society might influence what is to be researched, the research process itself, and communication of scientific results.

4.1 What is to be researched?

Patrons of post-academic science will focus on utility when deciding what projects to support, leading to the possible influence of vested interests on post-academic scientists. However, academic scientists are also affected by vested interest, social needs and power structures in their surroundings. Ziman (2000) asserts that

> academic scientists typically neglect socially 'uninteresting' problems - that is, problems which relate to the welfare of relatively inarticulate social groups or whose answers might turn out to be embarrassing to strong vested interests in society at large. (p. 171)

If we compare Millikan's research with post-academic science, we get the following picture: In this case the research budget and the need for external funding were probably minute. The research agenda was defined by Millikan himself, and the aim was to contribute to the development of the discipline. There was probably no foreseeable relevance for practical applications or policy-making. The most important vested interest was probably Millikan's desire for recognition as a scientist.

Narratives of academic science cannot normally illustrate the role of patrons and considerations of utility in defining research agendas in post-academic science. However, in a science curriculum for democratic participation, this is an important aspect. Answers to questions about unwanted effects of pollution and commercial products (e.g. gene-modified crops, food-additives, dioxins in fish) are important for many actors involved in socioscientific issues, including commercial firms, government, private organizations and citizen groups. Consequently, research might be initiated based on the idea that results might be used as arguments in debates about the possible risk. The role of science in disputes over lead in petrol and health effects from smoking illustrates this point. In addition, social power can be exercised to prevent the initiation of an investigation whose results might turn out to be acutely embarrassing. For the engaged citizen, this insight can make them realize that scientific knowledge costs money, and the argumentative imbalance might be due to imbalance of the power and resources available to the participants in the debate.

Although academic and post-academic science differ regarding the strength of the influence of patrons, the more general question, ''Why was this study undertaken?'', might be posed also regarding academic science. As in the case of Millikan and Ehrenhaft, publication and recognition by peers might be driving forces behind research, and these interests are also important to be aware of. One reason is that it can make students aware that there are always vested interests to be identified. Once aware of these, it is easier to evaluate a claim and its possible one-sidedness. To illustrate the possible role of patrons' interests in post-academic science a supplementary case study can be made. By contrasting e.g. the battle over the electron with a narrative from post-academic science, students' can comprehend the changing role of interests in science and that the reliability of scientific claims can vary.

4.2 Might values influence interpretation of data?

One might agree that observations and theories are mutually dependent, but does this also imply that values have an impact on the researcher's interpretations? Scientific criteria, including general epistemic values, obviously influence theory choice and interpretation in science. However, when theories conflict and different criteria lead to different judgment, there is a logical gap allowing for different interpretations. To fill this gap scientist need to use non-epistemic values, e.g. to decide what scientific criteria to emphasize. According to Longino (1990), scientific research in general involves background assumptions guiding the researcher's general perspective and interpretations.

The principal claim, that non-epistemic values can influence interpretation in science, can in general be illustrated using narratives from history of academic science. In the battle over the electron, we saw how Millikan's and Ehrenhaft's personal philosophies influenced their interpretations and their (published!) results, if not the consensual outcome of their research. Moreover, the narrative might also be used to illustrate how the concept of the electron and the claim that electric charge is quantified in the end became transformed into consensual science. The difference in reliability between results from the frontiers of science and consensual science can therefore be illustrated. This insight is of relevance when examining socioscientific issues where frontier science and single studies are used in arguments put forward. The relative difference in reliability between frontier science and consensual science holds for both academic and post-academic science. However, the vested interests involved will in general be more related to practical policy and backed by more resources, making examination of cases of post-academic science involved in controversy important.

At least as important as interpretation of data is probably research design. When designing a study it is sometimes possible to increase the possibility of certain desired results. As examples, Kjaergard and Als-Nielsen (2002) discuss how different ways of designing comparative studies in medicine affect the outcome, and Shrader-Frechette and

McCoy (1992) discuss preference of type II versus type I hypothesis in studies of environmental effects of chemical substances.

In their account of changing modes of scientific knowledge production, Funtowicz and Ravetz (1993) state that research seeking to inform political decision-making on socio-scientific issues sometimes faces high system complexities. In addition, when highly important societal decisions are involved the impact of non-epistemic values becomes unavoidable. This kind of science, where the system complexities and the decision stakes both are high, they label *post-normal science* (Funtowicz and Ravetz 1993). Typical examples are research on BSE (mad cow disease), the climate issue, and power transmission lines and health risk. They state that in post-normal science the researchers, due to the high system complexities, have to make decisions influenced by non-epistemic values in order to produce knowledge relevant for political decision-making (e.g. within political time constrains and including assumed consequences of different actions). Important science-related questions with a value dimension are, for instance: How can one simplify a problem and still produce policy-relevant information? Is the anticipated scientific information of a high enough quality to include it into the policy process at all? How precautionary do we wish to be? When designing studies, should researchers ask whether a suggested negative effect on the environment can be proved, or should they turn the burden of proof around, and ask whether a product can be proved to be environmentally safe?

The role of non-epistemic values are thus even more pronounced in Funtowicz's and Ravetz's (1993) concept of post-normal-science than in Ziman's (2000) concept of post-academic science. The impact of non-epistemic values in post-normal science cannot be removed or cancelled out by criticism or competing studies; it is a condition for doing the research within the constrains set by time and resources. As the scientific claims produced are dependent on the assumptions made, the scientific claims become 'soft' and sensitive to criticism. Moreover, actors with high stakes might exploit all possible uncertainties in the defense of their interests. As a result, claims from post-normal science typically have contested reliability, although trustworthiness is needed in the political process.

Awareness of the difficulties in reaching consensus when both system complexities and level of criticism are high is important when judging scientific claims involved. There might for instance be a real risk involved in a practice even if research results meet methodological criticism from some stakeholders' scientists.

Obviously, narratives from academic science cannot illustrate this kind of science–society interactions. In the battle over the electron, it was possible for Millikan, through hard work, to identify and minimize uncertainties involved. Moreover, outside the involved scientific community, no individuals or institutions probably had high decision-stakes in the questions involved. Concerning the possible role of non-epistemic values in the research process, the difference between the traditional and the new mode of science can therefore be substantial, especially if the system complexities are high. However, influence of non-epistemic values is also possible in academic science, especially at the frontier of research. Cases from the history of academic science can therefore be used to illustrate the basic idea; that non-epistemic values might influence scientific research. From a pedagogical point of view, it is even *advisable* to focus on academic science before learning about the nature of post-academic science. Not only because the latter proceeded the former in time, but also because it might be harder to grasp the role and significance of the science–society aspects in post-academic science without a general understanding of its predecessor. For example, if we want students to discuss how ''commercial values'' might influence interpretation of data, a basic understanding of the complex interplay between observations and theory and the role of background assumptions is necessary.

Nevertheless, the special characteristics of scientific research in cases where the system complexity and the decision stakes are high imply that a science curriculum for democratic participation also need to include case studies of contemporary issues involving science with post-normal characteristics.

4.3 Are communicated results trustworthy?

In his papers, Millikan gave many details of how the research and the calculations were done. Publication of results made it possible for Ehrenhaft to criticize Millikan's way of calculating the elementary charge in his first paper. Academic scientists, whose main interests are recognition and curiosity, can often be expected to give information about all relevant scientific arguments in controversy. However, according to Ziman (2000),

> post-academic natural scientists can usually be trusted to tell 'nothing but the truth', on matters about which they are knowledgeable. But unlike academic scientists, they are not bound to tell 'the whole truth' (p. 177)

This difference indicates that narratives describing academic science are not sufficient if we want to illustrate the nature of science involved in current socioscientific issues. Moreover, the fourth tenet discussed earlier stated that argumentation is an important part of science. However, free argumentation presupposes openness and publication. In post-academic science, researchers sometimes have to practice delayed publication, and commercial firms and governments have been accused of holding back results not favoring their policy on an issue.

Consequently, when including narratives from academic science in the curriculum, one needs to be aware of possible differences in openness between academic and post-academic science. From a pedagogical point of view, however, such differences also represent a positive option. After studying a narrative from academic science, one might inspect a current scientific controversy involving post-academic science and vested interests. By contrasting the results of the two inquiries, students can more easily identify and comprehend differences between the two types of science. Such comparison might make students appreciate argumentation and openness as important in science. In turn, this insight might stimulate them to demand disclosure of details when engaged in issues where unpublished post-academic science is being used in arguments. Insight into the nature of post-academic science might create an awareness of the weakened support for the idea of scientists as neutral and objective. Hopefully, based on this insight, more citizens will cross-check information and seek several accounts of scientific issues involved in a controversy.

5 Choice of perspective

Having discusses possibilities and challenges in using the history of science, I will put down one additional note of warning. All stories may be told in several different ways, with different emphasizes and from different perspectives. In my introductory example, I tried to exemplify two different ways of telling the Millikan story. The former of these was an account of Millikan's famous oil drop experiment, including a comment stating that Millikan demonstrated the charge of the electron to be quantified. In this version of the story, the context was minimized. Millikan is portrayed as a brilliant scientist working alone in his laboratory, discovering the secrets of nature. The latter account of the Millikan story focused on the ‘‘battle’’ between two competing groups of researchers, building on different philosophical and physical assumptions. That version also focused on Millikan’s struggle to get accurate and convincing results, and on the interplay between theory and observations.

Different choices of depth and perspective must be assumed to have a decisive impact on the learning outcome. The simplified version of the Millikan story involves a realist ontology and naïve positivist epistemology. Individualistic perspectives, while being common in science textbooks, often under-emphasise the collective and institutional dimension of science (Ziman 1980). A superficial treatment of the history of science might easily result in ‘‘fictionalized idealizations’’ (Monk and Osborne 1997, p. 406) where currently accepted views are seen as the most high-grade, leaving little recognition and respect for the creativity of scientists of the past. Therefore, if an adequate image of science is to be conveyed, elaborated accounts which includes the important and convincing details is needed.

6 Conclusions

Science for democratic citizenship presupposes relevant knowledge in addition to skills and attitudes. The basic assumption behind this article is the relevance of insight into NOS and science–society interactions for thoughtful examination and argumentation in socio-scientific issues.

The provisional and human character of science and the role of social processes and values in the development of scientific knowledge are basic insights from studies into NOS. Awareness of the social aspects of science can help citizens to engage in socioscientific issues based on a deeper understanding of the legitimacy of debating scientific claims. These insights might also facilitate an appreciation of expert disagreement as a source of arguments and an awareness of the role of uncertainty, the lacking intersubjectivity of single studies, and the need for confirmatory studies, debate and time to clarify complex scientific issues.

In addition, an awareness of the existence of different modes of scientific research and of the role of funding and vested interests in post-academic science is important. Such insights can foster more adequate judgments of science experts’ utterances, awareness of the possibility of funding research in support of certain perspectives on issues, and an understanding of the importance of demanding disclosure of assumptions and vested interests.

6.1 Focusing on common characteristics

Based on Ziman’s account of the changed and diversified nature of science, I have claimed that the relevance of the history of science for illustrating science involved in socioscientific issues today is not obvious. However, today academic and post-academic science coexists (Ziman 2000), and the two modes of science have many common characteristics. In addition, not only frontier science from post-academic science but also consensual academic science is often relevant to socioscientific issues. Examples here are the greenhouse effect in the climate debate and the possibility of induced radioactivity in irradiated food. When teaching about the disputability of science it is important also to make students understand the reliability of consensual science which have withstood attempts of criticism.

Discussing the battle over the electron, I concluded that the three first tenets about NOS stated earlier (scientific concepts are constructed by humans, observations and theories are mutually dependent and measurements and results always involve uncertainties) holds for both academic and for post-academic science. Where academic and post-academic science have common characteristics, cases from the history of science have certain pedagogical advantages as a context for learning. Post-academic science often involves advanced scientific concepts extending the science curriculum, and the number of researchers, subprojects and patrons typically involved adds to their complexity. When scientific research are relevant for socioscientific issues with high decision stakes, the presence of engaged citizens and organizations, counter-experts and media increases the complexity further. Although sophisticated ideas are involved, academic science offers cases with less complexity. The battle over the electron exemplifies this. That narrative makes the presence and role of Ehrenhaft's and Millikan's background assumptions and the complex interaction between data and theory evident. Although the stakes might be higher and the vested interest weaker than in post-academic science, the fundamental point about the underdetermination of theory by data is illustrated.

Consequently, narratives from the history of science can offer a transparency that is important from a pedagogical point of view. Examples are convincing only if students understand the example itself, including the telling details. Students need to understand methodological and scientific ideas involved if the case is to work as an example. Low complexity is also important as complex issues demand allocation of more teaching time and higher level of student engagement if a sufficient level of clearness is to be reached. Thus narratives from the history of science, due to their transparency, might be used to facilitate comprehension of characteristics of post-academic science.

6.2 Comparing academic and post-academic science

In addition to common characteristics, academic and post-academic science differ, as discussed, in many respects. The two modes of science differ in the role of funding and focus on utility, and in the subsequent possible influence of interests on the research agenda, on interpretations and on communication of results. Typically, science–society interactions are stronger and more complex in post-academic science. In addition, the complexity is often higher.

Nevertheless, from a pedagogical perspective I identified two possible advantages of including cases of academic science when teaching the nature of post-normal science also when their characteristics differ. Firstly, cases of academic science can be included prior to a focus on post-academic science. This makes it possible, when shifting to a case of post-academic science, to compare interesting aspects of the two modes of science. The use of comparison between contrasting examples is a powerful didactical strategy when characteristic aspects of phenomena are to be identified. As is the case in qualitative research, examination focusing on similarities and differences is an analytical strategy that facilitates comprehension. The focus on utility and funding in post-academic science is easier to grasp if compared to e.g. the driving forces in the history of the battle over the electron. In addition, comparison is necessary if students are to understand that today different modes of scientific research co-exist.

Secondly, some characteristics of post-academic science may be hard to comprehend if not based on a prior understanding of academic science. For example, students need to understand the norms and practices of openness, publication and argumentation before they can fully comprehend the consequences of less openness in post-academic science. Moreover, the possible influence of non-epistemic values needs to be based on an understanding of how publication and mutual criticism, as in the case of Ehrenhaft and Millikan, have the potential of canceling out personal bias inherent in single studies. Without such a background, the possible influence of non-epistemic values on scientific research might easily be over-interpreted and lead to a relativistic view of scientific knowledge where the idea of differences in level of reliability gets lost. Consequently, insight into academic science can pave the way for a more nuanced understanding of post-academic science.

6.3 Possible pitfalls

In this article, I have identified possible ways of using narratives of the history of academic science for illustrating aspects of NOS involved in socioscientific issues. Due to the existence of different modes of scientific research, such use is not without pitfalls.

If narratives of academic science are used as defining examples as to what characterizes science, the learner might develop an image of science which is misleading when confronted with post-academic science in topical socioscientific issues. Although common aspects between academic and post-academic science do exist, just to inform the students about the dissimilarities is not enough. Thus, the inclusion and analysis of cases of academic science need to be supplemented by similar analysis of cases of post-academic science. The latter might perfectly well be a topical socioscientific issue as this is a main focus for science education for citizenship. Obviously, some science teachers might want to take advantage of using ''ended stories'' where the political sensitivity has diminished and all aspects might be examined. However, post-modern science has been around for more then half a century, making it perfectly possible to study post-academic science and socioscientific issues from history. The research and debates about ozone depletion, smoking, asbestos and lead in petrol are cases in point.

Moreover, when using narratives from the history of academic science, science teachers need to be careful. S/he should either select cases where it is possible to focus on aspects common to both modes of scientific research, or include a case study of post-academic science and compare the two cases. Furthermore, to avoid reinforcing misconceptions about the separation of science from society, science–society interactions should be included also when using narratives from academic science.

Whatever narratives from the history of science a science teacher chooses to use, s/he needs to be aware that it is also important to choose narratives that involve enough depth, details and societal context to illustrate a sophisticated account of NOS. Superficial accounts will easily reinforce a naïve positivistic view of science, and is worse than no inclusion of the history of science at all.

Finally, science teachers need to be aware of the implicit epistemology in their teaching. However, the use of historical narratives has a potential advantage in this respect. A detailed historical account makes it possible to focus on evidence and argumentation by asking students whether a claim about NOS is supported by that example. Moreover, by including discussions about justifications of claims, the teaching will implicitly communicate a valuable message about the importance of debating knowledge claims.

6.4 Understanding post-academic science through the history of science

The history of science represents a rich reservoir of examples and illustrations suitable for the teaching of NOS and science–society interactions. It also offers a possibility to contextualize and humanize (Irwin 2000; Thomsen 1998). Moreover, the study of historical cases also has the potential of conveying depth in the learner's understanding of these different topics.

Throughout this article, I have been able to use the Millikan story to illustrate different arguments for the inclusion of the history of science in a science curriculum for citizenship. This, I believe, supports my main claim: That the history of science, also in the age of post-academic science, provides possibilities to illustrate and to concretize a range of topics relevant to science education for democratic citizenship. Topics of relevance included the nature of scientific research as practiced in the laboratory, aspects of the nature of communal dimensions of science, and some aspects of the interplay between scientific research and the wider cultural and societal context.

However, I have also argued that a science curriculum for citizenship needs to focus on the kind of science involved in socioscientific issues. This implies the inclusion of the nature of post-academic science. The need for science education to reflect the historical changes in NOS has been argued strongly by several science educators (Aikenhead 1994; Jenkins 1992; Osborne 1997). Discussing the historical evolution of both science and science education, Aikenhead (1994) ask the pertinent question ''How much longer can 19th century school science masquerade as legitimate science?'' (p. 20). At the same time, I believe insight into academic science is not only important in itself, but also relevant for understanding its successor. Consequently, the use of narratives from the history of academic science needs to be combined with examinations of contemporary socioscientific issues that include post-academic science and controversial science in the making. Such a balance between historical and contemporary case studies is crucial for a science curriculum for democratic citizenship.

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