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History and philosophy of science as a guide to understanding nature of science

Historia y Filosofía de la Ciencia como una Guía para Entender la Naturaleza de la Ciencia

História e Filosofia da Ciência como um Guia para a Compreensão da Natureza da Ciência

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Abstract

Nature of science (NOS) is considered to be a controversial topic by historians, philosophers of science and science educators. It is paradoxical that we all teach science and still have difficulties in understanding what science is and how it develops and progresses. A major obstacle in understanding NOS is that science is primarily 'unnatural', that is it cannot be learned by a simple observation of phenomena. In most parts of the world history and philosophy of science are 'inside' science content and as such can guide our understanding of NOS. However, some science educators consider the 'historical turn' as dated and hence neglect the historical approach and instead emphasize the model based naturalist view of science. The objective of this presentation is to show that the historical approach is very much a part of teaching science and actually complements naturalism. Understanding NOS generally requires two aspects of science: Domain general and domain specific. In the classroom this can be illustrated by discussing the atomic models developed in the early 20th century which constitute the domain specific aspect of NOS. This can then lead to an understanding of the tentative nature of science that is a domain general aspect of NOS. A review of the literature in science education reveals three views (among others) of understanding NOS: a) Consensus view: It attempts to include only those domain-general NOS aspects that are the least controversial (Lederman, Abd-El-Khalick); b) Family resemblance view: Based on the ideas of Wittgenstein, this view promotes science as a cognitive system (Irzik, Nola); c) Integrated view: this view postulates that both domain general and domain specific aspects of NOS are not dichotomous but rather need to be integrated and are essential if we want students to understand 'science in the making' (Niaz). The following framework helps to facilitate integration: i) Elaboration of a theoretical framework based on presuppositions, guiding assumptions, and previous experience of the scientist; ii) Formulation of research questions; iii) Operationalizing heuristic principles; iv) Designing experiments; and v) Understanding NOS. Various examples from history of science are provided to show how understanding 'science in the making'

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is important in order to integrate domain general and domain specific aspects of NOS. It is concluded that the integrated view of NOS facilitates 'science in the making' as based on the postulation of alternative interpretations of experimental data, which are controversial and thus science is primarily a human enterprise.
Keywords: history, philosophy, nature of science.

Resumen

La naturaleza de la ciencia (NOS) se considera que es un tema controvertido por los historiadores, los filósofos de educadores de la ciencia y de la ciencia. Es paradójico que todos enseñar ciencia y todavía tienen dificultades para comprender lo que es la ciencia y cómo se desarrolla y progresa. Un obstáculo importante en la comprensión de la NOS es que la ciencia es sobre todo "antinatural", es decir que no se puede aprender mediante una simple observación de los fenómenos. En la mayor parte de la historia del mundo y la filosofía de la ciencia son contenido de la ciencia "dentro" y como tal puede guiar nuestra comprensión de la NOS. Sin embargo, algunos profesores de disciplinas científicas consideran el "giro histórico" como anticuada y, por tanto, el abandono del enfoque histórico y en su lugar hacen hincapié en el modelo basado en la visión naturalista de la ciencia. El objetivo de esta presentación es mostrar que el enfoque histórico es una parte muy importante de la enseñanza de la ciencia y de hecho complementa el naturalismo. La comprensión de la NOS requiere generalmente dos aspectos de la ciencia: dominio general y dominio específico. En el aula esto puede ser ilustrado por la discusión de los modelos atómicos desarrollados en el siglo 20 que constituyen el aspecto específico de dominio de la NOS. Esto puede conducir a una comprensión de la naturaleza provisional de la ciencia que es un aspecto general de dominio de la NOS. Una revisión de la literatura en la educación científica revela tres puntos de vista (entre otros) de entendimiento NOS: a) Vista Consenso: Se intenta incluir sólo aquellos aspectos NOS dominio general que son los menos controvertido (Lederman, Abd-El-Khalick); b) Vista aire de familia: Sobre la base de las ideas de Wittgenstein, este punto de vista promueve la ciencia como un sistema cognitivo (Irzik, Nola); c) Visión integrada: este punto de vista postula que tanto el dominio de dominio general y aspectos específicos de la NOS no son dicotómicas, sino más bien deben ser integrados y son esenciales si queremos que los estudiantes entienden 'la ciencia en la toma' (Niaz). El siguiente marco ayuda a facilitar la integración: i) Elaboración de un marco teórico basado en presuposiciones, los supuestos de guía, y la experiencia previa del científico; ii) La formulación de preguntas de investigación; iii) Operacionalización de principios heurísticos; iv) El diseño de experimentos; y v) la comprensión de NOS. Varios ejemplos de la historia de la ciencia se proporcionan para mostrar cómo la comprensión 'la ciencia en la toma' es importante con el fin de integrar dominio generales y de dominio de aspectos específicos de la NOS. Se concluye que la visión integrada de la NOS facilita 'la ciencia en la toma "como basado en la postulación de interpretaciones alternativas de los datos experimentales, que son controvertidos y por lo tanto la ciencia es ante todo una empresa humana.
Palabras Clave: historia, filosofía, naturaleza de la ciencia.

Resumo

Natureza da ciência (NOS) é considerado como sendo um tema controverso por historiadores, filósofos de educadores de ciências e ciências. É paradoxal que todos nós ensinar ciência e ainda têm dificuldade em compreender o que é ciência e como ela se desenvolve e progride. Um grande obstáculo na compreensão NOS é que a ciência é essencialmente "não natural", isto é, não pode ser aprendido através da simples observação dos fenômenos. Na maior parte da história do mundo e filosofia da ciência se contentam ciência "dentro" e, como tal, pode guiar nossa compreensão da NOS. No entanto, alguns educadores de ciências consideram a "virada histórica", como antiquado e, portanto, negligenciar a abordagem histórica e em vez disso enfatizar o modelo baseado visão naturalista da ciência. O objetivo desta apresentação é mostrar que a abordagem histórica é uma parte muito importante de ensinar a ciência e, na verdade, complementa naturalismo. Compreender NOS geralmente requer dois aspectos da ciência: específico geral e de domínio Domínio. Na sala de aula o

que pode ser ilustrado por discutir os modelos atômicos desenvolvidos no início do século 20 que constituem o aspecto específico de domínio de NOS. Este pode, então, levar a uma compreensão da natureza experimental da ciência que é um aspecto geral de NOS domínio. Uma revisão da literatura na educação científica revela três pontos de vista (entre outros) de entendimento NOS: a) visão de consenso: Ele tenta incluir apenas os aspectos NOS domínio geral que são o menos controverso (Lederman, Abd-El-Khalick); b) vista semelhança de família: Com base nas ideias de Wittgenstein, essa visão promove a ciência como um sistema cognitivo (Irzik, Nola); c) Visão integrada: esta visão postula que tanto domínio gerais e domínio aspectos específicos da NOS não são dicotômica mas precisam ser integradas e são essenciais se queremos que os alunos a compreender a "ciência na tomada '(Niaz). O quadro a seguir ajuda a facilitar a integração: i) Elaboração de um quadro teórico baseado em pressupostos, guiando pressupostos e experiência anterior do cientista; ii) Formulação de questões de pesquisa; iii) princípios heurísticos Operacionalização; iv) Projetando experimentos; e v) Entendimento NOS. Vários exemplos da história da ciência são fornecidos para mostrar como o entendimento "ciência na tomada 'é importante, a fim de integrar os aspectos específicos da NOS domínio geral e de domínio. Conclui-se que a visão integrada da NOS facilita a "ciência na tomada de decisões", como base na postulação de interpretações alternativas de dados experimentais, que são controversos e, portanto, a ciência é essencialmente um empreendimento humano.
Palavras chave: história, filosofia, natureza da ciencia.

Introduction

It is paradoxical that we all teach science and still have difficulties in understanding what science is and how it is practiced, develops and progresses. A review of the literature shows that in most parts of the world students and teachers do not have an adequate epistemological understanding of nature of science (NOS) and consequently it continues to be an important area of research and of considerable interest to science educators (Abd-El-Khalick, 2012; Chang, et al., 2010; Deng, et. al., 2014; Hodson & Wong, 2014; Lederman, 2007; McComas et al., 1998; Niaz, 2016; Smith & Scharmann, 2008; Vesterinin & Aksela, 2013). In order to facilitate students' and teachers' understanding of nature of science (NOS) it is essential that they are provided with a glimpse of scientific practice imbued with arguments, controversies, and competition among rival theories and explanations (Niaz, 2012).

Wolpert (1993) a developmental biologist has referred to the difficulties involved in understanding scientific practice due to the *unnatural nature of science:*

> […] both the ideas that science generates and the way in which science is carried out are entirely counter intuitive and against common sense --- by which I mean that scientific ideas cannot be acquired by simple inspection of phenomena and that they are often outside everyday experience. Science does not fit with our natural expectations. (p. 1)

Indeed, most science curricula and textbooks reduce 'scientific practice' to a 'simple inspection of phenomena.' Let us consider two examples from the history of science to show that such reduction does not facilitate students' understanding of scientific practice. Most textbooks in almost all parts of the world report Rutherford's (1911) alpha particle experiments, which led to the postulation of the nuclear model of the atom. However, most textbooks ignore that J.J. Thomson (Rutherford's teacher and colleague) at about the same time, conducted very similar alpha particle experiments at the Cavendish Laboratory. Although, both Rutherford and Thomson found very similar experimental results and still their interpretations were entirely different which led to a bitter dispute between the two protagonists, that lasted for many years (for details, see Niaz, 2009; Wilson, 1983). Rutherford postulated the hypothesis of single scattering whereas Thomson postulated the hypothesis of compound scattering. This shows that a 'simple inspection of phenomena' did not help Thomson and Rutherford to resolve the controversy and thus understand the experimental data.

Another example is provided by experimental data that led to the determination of the elementary electrical charge by R. Millikan and F. Ehrenhaft in the period 1909-1925 (Holton, 1978; Niaz, 2005). Although, both researchers had very similar experimental data, inspection of phenomena was far from simple, as Millikan postulated the existence of a universal electrical charge (the electron), and Ehrenhaft postulated the existence of fractional electrical charges (sub-electrons). At this stage it can be argued that the two examples provided here refer to historical episodes that took place almost 100 years ago, and that this is not how science is done in modern times. Interestingly, a recent study has highlighted the need for science teachers to go beyond the myth that 'seeing is believing', in cogent terms:

> It is still not common for teachers to discuss the ways in which experiments, as well as observations, are theory impregnated or to point out that we can only investigate what we have speculated about, and in terms of how we have speculated about them. In a sense, as our respondents repeatedly told us, theoretical assumptions bias the inquiry and prejudice the conclusions. In consequence the notion of absolute scientific objectivity is a myth. Observational and experimental data do not 'speak for themselves'; all data have to be interpreted. (Wong & Hodson, 2009, p. 124, italics in original)

It is important to note that this study is based on thirteen well-established and active scientists from different parts of the world, in fields such as astrophysics, experimental particle physics, molecular biology and cancer research. In a similar vein Schwab (1974) has emphasized the role played by 'heuristic principles' both in understanding and teaching science:

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

In the examples presented above, the heuristic principles would be the existence of the nuclear atom (Rutherford & Thomson) and the universal charged particle (Millikan & Ehrenhaft).

The objective of this article is to argue for the inclusion of history and philosophy of science in the science curriculum, in order to go beyond a 'simple inspection of phenomena' and understand the underlying heuristic principles.

History and Philosophy of Science are 'Inside' Science

It is important to recognize not only the role played by history and philosophy of science but also that these aspects are already present in the science curriculum and even the textbooks, albeit without the necessary context to understand the nature of science (Bevilacqua & Bordoni, 1998; Matthews, 2015; Niaz & Rodríguez, 2001). Domain-general aspects of NOS have been the subject of considerable research in science education (Lederman et al., 2002: McComas *et al*., 1998). Following are some examples of how domain-general aspects of NOS can be related to the domain-specific context of the science curriculum (see table 1).

Dilemmas for Science Education

Despite some consensus the role of history of science and the relationship between the domain-general and domain-specific aspects of NOS are controversial issues. For example, two distinguished science educators have argued that current philosophy of science has gone beyond the historical turn (Kuhn, Lakatos, Laudan) and now espouses a naturalist philosophy of science, and

Table 1. Relationship between domain-general and domain-specific aspects of NOS[2].

Domain General	**Domain Specific**
Empirical	Determination of mass-to-charge ratio of cathode rays / Oil drop experiment
Rival theories	Valence bond and molecular orbital models of chemical bonding / Copenhagen, Schrödinger and de Broglie hypotheses of quantum mechanics
Alternative interpretations	Alpha particle experiments / Oil drop experiment / Statistical and phenomenological models of thermodynamics
Theory-laden	Determination of elementary electrical charge: Millikan's and Ehrenhaft's presuppositions
Tentative	Atomic models in the 20th century / From Newtonian mechanics to Einstein's theory of relativity
Objectivity	Alpha particle experiments / Oil drop experiment / Bending of light in the 1919 eclipse experiments
Social and historical milieu	Michelson-Morley experiment

suggested that the views of those who emphasize history of science are, "Grounded in dated (logical positivism and historical turn) views that depict NOS through heuristics that focus on individual scientists justification of knowledge" (Duschl & Grandy, 2013, p. 2125). This may not only surprise many science educators and may even be disconcerting to those who are beginning their careers in science education. In contrast, Matthews (2015) has argued for just the opposite:

> Clearly, the history of science should be used to illustrate positions arrived at in philosophy of science. An exposition of the nature of science, of theory evaluation or the ontological commitments of science that did not make mention of Galileo, Newton, Kepler, Lavoisier, Darwin, Mendel, Mach or Einstein, and the scientific controversies they engendered, would be very odd. (p. 4)

Another dilemma faced by the science education community is the relationship between domain-general and domain-specific aspects of the history and philosophy of science and more specifically NOS. Are these aspects dichotomous or can these be integrated? (see Table 1 for some examples). Lederman and colleagues have generally emphasized the domain-general aspects of NOS through the application of the views of nature of science questionnaires (Abd-El-Khalick, 2012: Lederman, et al., 2002; Smith & Scharmann, 1999). On the other hand, some science educators have emphasized the domain-specific aspects of science (Erduran, 2007; Wong & Hodson, 2009). These dilemmas pose considerable difficulties for the introduction of NOS in the classroom.

Different Views of Understanding Nature of Science

Consensus View

Based on a critical review of science standards documents, history and philosophy of science literature this view fosters a consensus among different research communities. It attempts to include

2. This is a selected list of NOS aspects. More detailed information can be found in Lederman et al (2002), McComas et al (1998), Niaz (2009, 2016).

only those domain-general NOS aspects that are the least controversial (Lederman, et al., 2002; Osborne et al., 2003). Matthews (2015) has suggested that these aspects be referred to as Features of Science (FOS), which are more flexible and easier to include in the classroom.

Family Resemblance View

Based on the ideas of Wittgenstein, this view promotes science as a cognitive system in which classroom activities are organized around questions such as: How does observation differ from experimentation? What is the point of doing an experiment and how does it relate to theory? (Irzik & Nola, 2011). This view neglects the history of science and hence the science curriculum. It is quite similar to the model based view of Duschl and Grandy (2013).

Integrated View

Based on a history and philosophy of science perspective, this view postulates that both domain-general and domain-specific aspects of nature of science are not dichotomous but rather integrated and are essential if we want our students to understand 'science in the making' (Niaz, 2001; 2012). According to Niaz (2001): "It is concluded that nature of science manifests in the different topics [domain-specific] of the science curriculum as heuristic principles. Science education, by emphasizing not only the empirical nature of science [domain-general] but also the heuristic principles, can facilitate conceptual understanding" (p. 784). Now let us consider, what does integration mean?

a. Elaboration of a theoretical framework based on presuppositions, guiding assumptions, hard-core beliefs, and previous experience.
b. Formulation of research questions
c. Operationalizing heuristic principles
d. Designing experiments
e. Understanding nature of science

This sequence of steps is not an algorithm, but rather an outline of how science content can be organized around domain-general and domain-specific aspects of science.

Teaching Empirical Nature of Science

In order to teach about the empirical nature of science (a NOS aspect) a teacher may select the topic of the determination of the elementary electrical charge based on the oil drop experiment (developed by Robert Millikan, 1917). The integrated view of teaching NOS would suggest the following sequence of steps (these steps can of course vary according to the needs of a topic):

a. Millikan's theoretical framework (presuppositions)

All atoms have a universal charged particle based on J.J. Thomson's determination of the charge to mass ratio (found to be constant) of cathode rays emitted by different metals.

b. Research questions

Do all atoms possess similar constituents? Is there a primordial sub-atom out of which atoms are made?

c. Operationalizing heuristic principles

The charge on the oil drop could have been a statistical mean of particles having varying charges or a discrete particle with a definite charge in all experiments.

d. Designing experiments

Millikan did not design the experiment but, rather, discovered it. It took many years to refine the experimental procedure leading to a running controversy with Felix Ehrenhaft.

e. Understanding nature of science (Holton, 1978; Niaz, 2005).

Teaching Objectivity in Science

Teaching about objectivity is perhaps one of the most difficult and controversial topic in the science curriculum. Within a historical perspective, Daston and Galison (2007) have explored the complexities of the issues involved in the following terms:

> To grant objectivity a history is also to historicize the framework within which much philosophy, sociology, and history of science has been cast in recent decades. The opposition between science as a set of rules and algorithms rigidly followed versus science as tacit knowledge (Michael Polanyi with a heavy dose of the later Ludwig Wittgenstein) no longer looks like the confrontation between an official ideology of scientists as supported by logical positivist philosophers versus the facts about how science is actually done as discovered by sociologists and historians. Instead, both sides of the opposition emerge as ideals and practices with their own histories --- what we have called mechanical objectivity and trained judgment" (p. 377).

Indeed, this sets the stage for understanding progress in science within a much richer context, in which mechanical objectivity would approximate to the ideals of logical positivism and trained judgment to how science is actually done. Interestingly, Daston and Galison (2007, p. 478) consider the controversy with respect to the determination of the elementary electrical charge between Millikan and Ehrenhaft (Holton, 1978) as an example of trained judgment.

In this context the following examples could help to understand objectivity within a historical context:

a. *Alpha particle experiments and the controversy between Rutherford and Thomson*. If experimental data could be understood by following a set of rules and algorithms (that is mechanical objectivity) there would have been no controversy between these two leading scientists (I have provided some details in the introduction section). Instead, the scientific community had to go beyond and follow some form of trained judgment to resolve the controversy.
b. *Oil drop experiment and the controversy between Millikan and Ehrenhaft*. As suggested by Daston and Galison (2007) this would also provide an example of trained judgment.
c. *Bending of light in the 1919 eclipse experiments*. Eddington's (Dyson et al., 1920) interpretation to support Einstein's theory was far from convincing. Consider the following scenario: Suppose Edington was not aware of Einstein's General Theory of Relativity and particularly of the prediction that sunlight near the sun would bend. Under these circumstances experimental evidence from all the experiments (Sobral and Principe) would have been extremely uncertain, equivocal and difficult to interpret (for details, see Niaz, 2009, chapter 9, pp. 127-137).

According to Machamer & Wolters (2004): "... to save the objectivity of science, we must free it from an ideal of rationality modeled after mathematics and logic; we must show that both rationality and objectivity come in degrees and that the task of good science is to increase these degrees as far as possible (pp. 9-10). Similar ideas with respect to objectivity are difficult to accept in science education. However, it seems that some changes can be observed on the horizon as can be seen from Wong and Hodson (2009) cited above.

Teaching Social and Historic Milieu

Michelson-Morley experiment provided a 'null' result with respect to the ether-drift hypothesis that is no observable velocity of the earth with respect to the ether (Michelson & Morley, 1887). Lakatos (1970) considers it to be the "greatest negative experiment in the history of science" (p. 162). Leon Cooper, Nobel Laureate in physics, has emphasized the importance of the historic milieu in the following terms:

> If, for example, the Michelson-Morley experiment had been done at the time of Copernicus, their (to them disappointing) result that they could measure no motion of the earth might have been greeted with a statement like, 'Why are you wasting your time? Everyone knows that the earth stands still at the center of the universe. Any attempt to measure its motion will give the answer you obtained: zero.' Think of what effect this might have had on astronomers at the time of Copernicus. (Reproduced in Niaz *et al.*, 2010, p. 45)

Based on a history and philosophy of science approach Leon Cooper's approach to teaching science could be summarized as:

- Context of an experiment
- Why the experiment was done
- Why the experiment was difficult
- How the ideas evolved

Conclusion

Examples provided in this article show that integration of domain-general and domain-specific of science content can facilitate the understanding of science from being unnatural (Wolpert, 1993) to natural. Cooper has helped to solve the dilemma by providing the following thought provoking insight:

> It seems obvious that questions take their meaning in the context of what people believe at the time, and if you don't communicate this, you really are not communicating why people did things, why it was difficult, and how the ideas that we now accept evolved. (Reproduced in Niaz *et al.*, 2010, p. 45)

No wonder, to understand science we need to seek the origin of ideas within a historical context. The degree to which the unnatural may become natural may depend among other factors, on our ability to engage the students with the historical context. Some of the historical episodes discussed in this article provide a glimpse and outline of how classroom practice can be changed to facilitate a better understanding of, for example Rutherford's nuclear atom (alpha particle experiments), determination of the elementary electrical charge (oil drop experiment), and Einstein's theory of relativity (eclipse experiments, Michelson-Morley experiment).

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