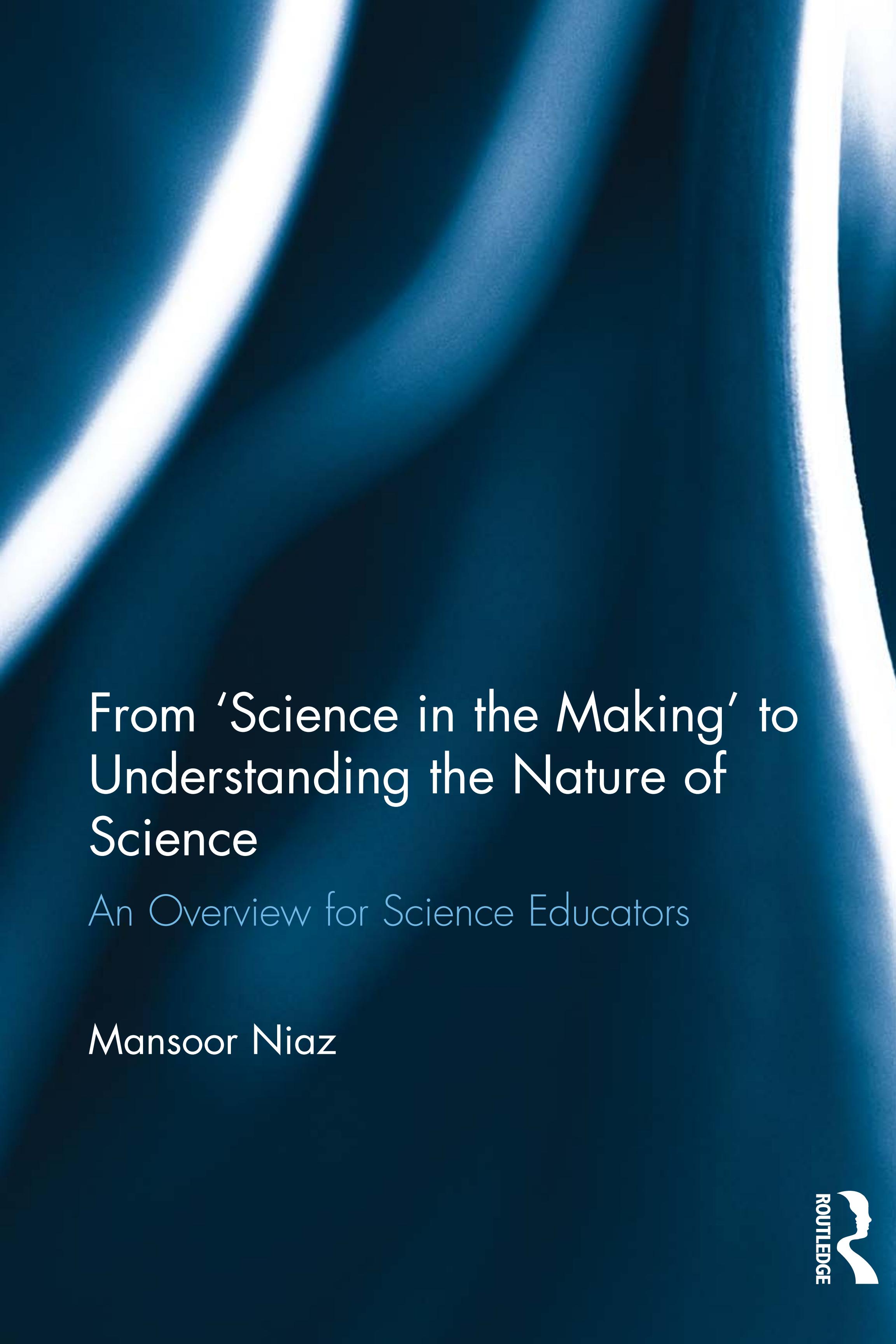

From 'Science in the Making' to Understanding the Nature of Science

An Overview for Science Educators

Mansoor Niaz

ROUTLEDGE

FROM ‘SCIENCE IN THE MAKING’ TO UNDERSTANDING THE NATURE OF SCIENCE

“It is clear the author knows a great deal about the relevant history of ‘science in the making’ and understands why this knowledge is important to students and teachers of science. The use of actual cases in the history of science to show how disagreements between scientists arise and finally are resolved will help students of science better understand the nature of science.”

Ronald G. Good, Louisiana State University, USA

“This useful resource for teacher educators and science education researchers collates in one volume the substance of a large body of the nature of science literature from multiple sources. It offers useful information for students wishing to review some of the important historical experiments pertinent to the science concepts presented in secondary and tertiary textbooks.”

Kevin de Berg, Avondale College, Australia

The nature of science is highly topical among science teacher educators and researchers. Increasingly, it is a mandated topic in state curriculum documents. This book draws together recent research on nature of science studies within a historical and philosophical context suitable for students and teacher educators. Traditional science curricula and textbooks present science as a finished product. Taking a different approach, this book provides a glimpse of ‘science in the making’—scientific practice imbued with arguments, controversies, and competition among rival theories and explanations. Teaching about ‘science in the making’ is a rich source of motivating students to engage creatively with the science curriculum.

Readers are introduced to ‘science in the making’ through discussion and analysis of a wide range of historical episodes from the early 19th to early 21st centuries. Recent cutting-edge research is presented to provide insight into the dynamics of scientific progress. More than 90 studies from major science education journals, related to nature of science are reviewed. A theoretical framework, field tested with in-service science teachers, is developed for moving from ‘science in the making’ to understanding the nature of science.

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Dedicated to the fond memories of my father, Niaz-Ud-Din Ahmad, who guided me into the historical labyrinths of Ibn-Khaldun and Toynbee, that intertwined at the same time.

CONTENTS

PREFACE

The rationale of 'science in the making' is based on a history and philosophy of science perspective which involves various interactive processes based on presuppositions of the scientist, alternative interpretations of the data, controversies among scientists having similar experimental data, inconsistencies involved in the construction of a theory, and the theory-laden nature of scientific knowledge. The history of science bears witness to these and the essence of science is best characterized by the creativity and imagination of the scientists. In contrast, the traditional science curriculum and textbooks espouse an entirely opposite strategy of presenting science as a finished product, in which students simply regurgitate experimental details. According to some researchers, such presentations constitute a "false" image of science, which is not conducive toward a better understanding of science. This leads to the question: Why do we deny our students an image of science based on how it is practiced by scientists ('science in the making')? Based on a critical analysis of various historical episodes, this book provides plausible answers.

The main objective is to familiarize students, teachers, and researchers with 'science in the making' through various historical episodes, such as: Discovery of the planet Neptune; Discovery of the elementary particle neutrino; Dalton's determination of the law of multiple proportions; Maxwell's kinetic theory of gases; Mendeleev's periodic table; Thomson's discovery of the electron; Rutherford's nuclear atom; Bohr's model of the atom; Millikan's determination of the charge of the electron; Millikan's determination of Planck's constant *h*; Determination of wave-particle duality by de Broglie; and Perl's determination of the Tau Lepton. This provides a rich landscape of scientific endeavor covering a period of over 200 years. Some of the salient features of this book:

a. It shows how 'science in the making' is a rich source of motivating students to engage creatively with the science curriculum.
b. It discusses and critically analyzes a wide range of historical episodes from Dalton (early 19th century) to Perl (early 21st century).
c. It presents recent cutting-edge research that provides insight into the dynamics of scientific progress (based on Nobel Laureate Martin Perl's discovery of the Tau Lepton).
d. It looks at how the views of Nobel Laureate Leon Cooper can influence in-service teachers' understanding of the nature of science.
e. It reviews over 90 studies from major science education journals (2004–2008), related to the nature of science.
f. It offers a theoretical framework developed and field tested with in-service science teachers: Presuppositions, Research questions, Heuristic principles, Designing experiments, and Understanding the nature of science.
g. It includes a new *scenario* in the classroom in which students and teachers could present arguments and counter-arguments based on historical reconstructions of various episodes in the history of science.

In writing this book my objective was not any particular course. This has the advantage that the book could be adopted for various types of courses, such as: Teaching the nature of science, Introduction to the history and philosophy of science, Research methodology. The book is rich in content-based issues related to various historical episodes. The intended audience for this book is secondary and university-level teachers, science teacher educators, researchers in science education, science methods course teachers, and students.

Chapter 2 establishes a relationship between 'science in the making' and heuristic principles within a historical context. Research relating to students' and teachers' understanding of the nature of science is reviewed in Chapter 3. Next, Chapter 4 explores the difficulties involved in introducing the nature of science to in-service chemistry teachers. Chapter 5 draws attention to the need for differentiating between experimental data and heuristic principles. How the views of Leon Cooper (Nobel laureate) can influence in-service science teachers' understanding of the nature of science is the subject of Chapter 6. Martin Perl's (Nobel laureate) perspective on the nature of science and teaching science is presented in Chapter 7. The contents of this book are organized around three main themes: (a) Chapters 2 and 3 deal with 'science in the making' in a historical context and with students' and teachers' understanding of the nature of science; (b) Chapters 4 and 5 explore the experiences of classroom teachers with respect to heuristic principles and the nature of science; and (c) Chapters 6 and 7 deal with two Nobel laureates' perspectives on the nature of science. Readers can select the chapters that address their particular interests.

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Like any intellectual endeavor this book has benefitted from the advice and support of many students, colleagues, and friends. My institution, Universidad de Oriente (Venezuela) has provided support for most of my research activities. Leon Cooper's (Nobel laureate, Brown University), perspective on the nature of science and the integration of history and philosophy of science within science textbooks was a major source of inspiration. Cooper's perspective facilitated the design of a teaching strategy for familiarizing science teachers with the nature of science (Chapter 6). Martin Perl (Nobel laureate, Stanford Linear Accelerator Center) has over the years been supportive of my work and especially with respect to "teaching science as practiced by scientists" (Chapter 7). I have benefitted from discussions and criticisms at different stages from: Fouad Abd-El-Khalick (University of Illinois, Champaign-Urbana), Stephen Klassen (University of Winnipeg), Liberato Cardellini (Università Politecnica delle Marche, Italy), and Michael R. Matthews (University of New South Wales).

I would like to thank the two reviewers who provided constructive criticisms and, at the same time, encouragement for completing the book.

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1

INTRODUCTION

Research in science education has recognized the importance of history and philosophy of science (HPS) for teaching science. A review of this research shows that most students and teachers do not have adequate epistemological views of the nature of science (NOS). This raises many issues, such as: (a) Why is it important to understand how science works? (b) Is it not sufficient for students to learn the content of science? (c) Do students have to learn how and why a scientist performed an experiment? (d) Does it help students to know that the same experimental data was interpreted differently by another scientist? (e) Do we present a false image of science in our textbooks and classrooms? (f) Is the false image of science conducive towards a better understanding of science? (g) Does the science curriculum motivate students to engage creatively and form part of a responsible citizenry? These issues impinge on the NOS and this book provides plausible answers. Hodson (2009) has emphasized the need for a science curriculum that deals with such NOS issues:

> We should ask why a false or confused NOS knowledge constitutes a major problem for science education. In short, why does it matter what image of science is presented and assimilated? It matters insofar as it influences career choice, and so may have long-term consequences for individuals. It matters if the curriculum image of science is such that it dissuades creative, non-conformist, and politically conscious individuals from choosing to pursue science at an advanced level . . . Failing to provide every student with an adequate understanding of the nature of science runs counter to the demand for an educative citizenry capable of responsible and active participation in a democratic society. *(pp. 142–143)*

Nobel laureate Kenneth G. Wilson[1] has similarly emphasized that history of science, “helps students considering science as a career to think, ask questions, and explore the concepts and ramifications of broad topics, enabling them to grasp what science is about and how it is conducted” (Gooday, Lynch, Wilson, & Barsky, 2008, p. 323).

Science textbooks have generally been found to emphasize the empiricist perspective according to which experimental findings unambiguously lead to the formulation of scientific laws and theories. The present state of our textbooks can be summarized in the following terms: “These trends are incommensurate with the discourse in national and international science education reform movements” (Abd-El-Khalick, Waters, & Le, 2008, p. 835). In a similar vein, Winchester (2006) has cautioned: “However one characteristic stands out for most textbooks in our own time, namely, that they are concentrated presentations of results of previous thought, thought that in fact had a long history. And that history is usually ignored” (p. 1).

This should be cause for concern for most science teachers and especially those interested in the HPS. Such a state of our textbooks is even more troublesome if in retrospect we consider what Holton warned almost four decades ago with respect to what he called the myth of *experimenticism*, namely scientific research as the inexorable result of the pursuit of logically sound conclusions from experimentally indubitable premises:

> Almost every science textbook of necessity places a high value on clear, unambiguous, inductive reasoning. The norm of rationalism in the classroom would seem to be threatened if the text were to allow that a correct inductive generalization may be made without unambiguous experimental evidence. Hence, the likelihood is *a priori* great that any pedagogic presentation of any subject will suggest a clear genetic link from experiment to theory. *(Holton, 1969, p. 974, original italics)*

More recently, historian and philosopher of chemistry Trevor Levere, addressing the 7th International History, Philosophy and Science Teaching Conference, Winnipeg, Canada, expressed a similar concern in cogent terms:

> many authors of science textbooks still write as if there were such a thing as *the* scientific method, and use labels like induction, empiricism, and falsification in simplistic ways that bear little relation to science as it is practiced. *(Levere, 2006, pp. 115–116, original italics)*

‘Science as it is practiced’ by scientists, as suggested by Levere, can indeed be an important guideline for science textbooks and teaching science. This leads to an intriguing question: Why do we deny our students the dynamics of scientific progress based on science as a human enterprise (‘science in the making’)? Of course, there is no simple answer to this question. One plausible answer could be that traditional science education does not comprehend the creative and contingent nature of science. Philosopher-physicist James Cushing (1989) has referred to this in the following thought provoking terms: “science is an historical entity whose practice, methods and goals are *contingent*. There may not be *a* rationality which is the hallmark or the essence of science” (p. 2, original italics. In a footnote Cushing explains what he means by *contingent*, “I simply mean not fixed by logic or necessity”, p. 20). This might sound sacrilegious to traditional science teachers and textbook authors. Holton, Levere, and Cushing are trying to present a historical perspective of how science is practiced by scientists, namely construction of a scientific theory involves various interactive processes such as: presuppositions of the scientist, alternative interpretations of data, controversies among scientists having similar experimental data, inconsistencies involved in the construction of a theory, and the theory-laden nature of scientific knowledge.

History of science bears witness to these difficulties and the essence of science is perhaps characterized by the creativity and imagination of scientists. Under this perspective, telling students that scientists are rational would be too simplistic and it would be more motivating to reconstruct the different historical episodes in order to illustrate ‘science in the making’ and how science is practiced by scientists (Niaz, 2010a). In other words, the construction of knowledge requires assumptions that support reasoning within a social and cultural context (Longino, 1990, p. 219). Discussion of historical episodes can provide students with an opportunity to glimpse the complexity of the scientific enterprise and appreciate how, “both rationality and objectivity come in degrees and that the task of good science is to increase these degrees as far as possible” (Machamer & Wolters, 2004, p. 9).

According to Schwab (1974) within a historical perspective, scientific enquiry is based on a conceptual structure of a discipline:

> The structure of a discipline consists, in part, of the body of imposed conceptions which define the investigated subject matter of that discipline and control its inquiries . . . we cannot, with impunity, teach the conclusions of a discipline as if they were about the whole subject matter and were the whole truth about it. For the intelligent student will discover in time—unless we have thoroughly blinded him by our teaching—that any subject behaves in ways which do not conform to what he has been told about it. *(p. 166)*

Translating this into an HPS context, the structure of a discipline would represent the guiding assumptions, theoretical framework, and presuppositions of the scientist. This helps the scientist to formulate research questions, operationalize heuristic principles, design experiments, and finally interpret the results. This process helps our understanding of the NOS. Actually, Schwab goes beyond by alluding to the changing nature of a discipline and hence the need to make students aware of it. This advice from Cushing (1989), Holton (1969), Levere (2006), and Schwab (1964) has not only been ignored but, rather, most science curricula and textbooks espouse an entirely opposite strategy of presenting science as a finished product (final form, cf. Duschl, 1990) based on a "rhetoric of conclusions," which does not facilitate our understanding of 'science in the making' and, hence, the NOS.

At this stage it is important to note that the NOS is an important area of research and of considerable interest to science educators. In a recent study Chang, Chang and Tseng (2010) analyzed the content of science education research based on the scientometric method of multi-stage clustering. These authors found a total of 3,039 articles from four major science education journals, namely *International Journal of Science Education*, *Journal of Research in Science Teaching*, *Research in Science Education*, and *Science Education*, during the period from 1990 to 2007. Multi-stage clustering facilitated the identification of nine important topics (clusters), of which "Conceptual change and concept mapping" had the highest number (n = 553) of articles. The next topic of importance was "Nature of science and socio-scientific issues" with 191 articles, published by authors from various countries around the world. Furthermore, in 1990 there were only two articles on NOS-related issues and this number increased to 25 in 2006. This clearly shows the increasing importance of the NOS for teaching science.

In order to facilitate students' and teachers' understanding of the 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 (cf. Niaz, Aguilera, Maza, & Liendo, 2002). Based on this perspective, the objective of this book is to explore 'science in the making' in order to understand the NOS and, consequently, to draw conclusions for teaching science. In this chapter I shall use two episodes from the history of science (discovery of the planet Neptune and the elementary particle the neutrino), to illustrate how 'science in the making' can be helpful for understanding the NOS.

Discovery of the Planet Neptune

Discovery of this planet is a good example for illustrating 'science in the making.' Neptune was the first planet to be discovered due to evidence that indicated that it was causing a gravitational effect leading to irregularities in the orbit of another planet, Uranus (discovered in 1781 by Friedrich W. Herschel). Thus, scientists predicted the existence of Neptune before it was observed (Grosser, 1962). In 1845, John C. Adams at St. John's College, Cambridge, estimated the orbit of the unknown planet to be beyond that of Uranus, and predicted that it could account for the irregularities in its motion. Later, Urbain J.J. Leverrier in France made similar calculations in 1846 and communicated them to the French Academy of Sciences and Johann G. Galle in Berlin, who discovered the planet on September 23, 1846. At the time of its discovery Neptune was only 1° from the place predicted by Leverrier and about 2½° from the place predicted by Adams.

Interestingly, Adams had communicated his calculations among others to the English astronomer James Challis at Cambridge. Challis undertook to verify the calculations of Adams and Leverrier, especially with respect to the existence of a new planet (for details, see Smart, 1946). Challis sighted the undiscovered planet (i.e., Neptune) at least four times during the summer of 1846 (once on August 4), that is before Galle. According to philosopher-physical chemist Michael Polanyi (1964), "these facts made no impression on him [Challis], for he distrusted altogether the hypothesis which he was testing" (p. 30). This clearly shows how lack of a belief in a presupposition (existence of Neptune) led Challis to ignore relevant experimental data.

Now let us see how a physicist-philosopher of science has interpreted the discovery of Neptune based on a conjecture:

> Leverrier and Adams [must have wondered] "Look here, the planet Uranus is not keeping time properly; the only way we can both acknowledge that fact and also save celestial mechanics is to suppose that there is another object, some "dark body," which has the following properties, a, b, c . . . etc." And they worked out the properties of this "in reverse," as it were. What would have to be the properties of a planet in order to perturb Uranus as it is perturbed? *(Hanson, 1964, pp. 166–167)*

This constitutes an interesting example of 'science in the making.' Early conjectures of Leverrier and Adams, subsequent discovery of Neptune by Galle, and the interpretation by Hanson, are all based on the premise that Newton's physics and especially the law of gravitation correctly described the orbits of the planets. Hanson (1958) pays tribute to the intellectual efforts of Leverrier in the following terms: "How remarkable that this man [Leverrier] should have raised classical mechanics to its highest pinnacle by predicting the unseen Neptune as being responsible for observed aberrations in the orbit of Uranus" (pp. 203–204).

Lakatos (1970) goes beyond and provides further insight by presenting an imaginary case of planetary misbehavior that elucidates how scientists do science:

> A physicist of the pre-Einsteinian era takes Newton's mechanics and his law of gravitation (N), the accepted initial conditions, I, and calculates, with their help, the path of a newly discovered small planet, p. But the planet deviates from the calculated path. Does our Newtonian physicist consider that the deviation was forbidden by Newton's theory and therefore that, once established, it refutes the theory N? No. He suggests that there must be a hitherto unknown planet p' which perturbs the path of p. He calculates the mass, orbit, etc., of this hypothetical planet and then asks an experimental astronomer to test this hypothesis. The planet p' is so small

> that even the biggest available telescopes cannot possibly observe it: the experimental astronomer applies for a research grant to build yet a bigger one . . . Were the unknown planet p' to be discovered, it would be hailed as a new victory of Newtonian science. But it is not. Does our scientist abandon Newton's theory and his idea of the perturbing planet? No. He suggests that a cloud of cosmic dust hides the planet from us . . . But the cloud is not found. Is this regarded as a refutation of Newtonian science? No . . . [and] yet another ingenious auxiliary hypothesis is proposed . . .. *(pp. 100–101)*

Motterlini (1999, p. 69) considers that the imaginary story of the planet related by Lakatos is based on many real historical instances including the discovery of Neptune. This story encapsulates many aspects of 'science in the making' and thus has implications for understanding the NOS, as follows: (a) When confronted with empirical evidence that seems to refute a scientific theory, scientists generally resist such a refutation and look for an alternative hypothesis; (b) The alternative hypothesis requires further experimental evidence (mass, orbit, and other characteristics of an unknown planet, for example the work of Adams and Leverrier in the case of Neptune); (c) The process of finding alternative hypotheses and looking for experimental support can continue for some time; (d) The role of these "auxiliary hypotheses" is to protect the guiding assumptions or hard-core of a theory (Newtonian theory in the present case); (e) Eventually, the hard-core of a theory crumbles and a new theoretical framework assumes the role of theory building (Einstein's general relativity theory, 1915, in the present case).

Discovery of the Elementary Particle Neutrino

Before 1930 it was generally believed that, based on Einstein's equation, $E = mC^2$, mass-energy is conserved in nuclear reactions. Based on this assumption, generally referred to as "energy conservation" whenever there is a change of mass in nuclear reactions, the difference shows up as kinetic energy, as indicated by Einstein's equation. By the end of the 1920s it was found that energy conservation does not seem to hold for beta decay reactions (changing a neutron into a proton and an electron in radioactivity), as about one-third of the energy seems to disappear. To uphold the law of conservation of energy it was postulated that another particle is emitted that carries off the missing energy. This implied the existence of particles called neutrinos, predicted as early as 1929 by W. Pauli, years before they were actually discovered.

Although the neutrino could not be detected for many years, it became important after Enrico Fermi presented his theory of beta decay in 1933 in which neutrinos (Italian for "small neutral one") are emitted and by 1940 it was used routinely by nuclear theorists (Kragh, 1999). Fermi's theory identified the weak nuclear force as being distinct from the strong nuclear force and responsible for beta decay. Interestingly, Fermi's ground breaking theory of beta decay, which founded the modern theory of weak interactions, was first rejected by *Nature*. Neutrinos are massless, chargeless, do not feel the strong nuclear force, and interact via the very short-ranged weak nuclear force. Recent research based on neutrino oscillations, however, has shown that neutrinos might have mass. Actually physicists believed in the existence of the neutrino even though it had not been detected, and for some it was simply a convenient way of organizing experimental data.

Despite the difficulties and a lack of interest in the experimental detection of the neutrino, in 1951 Frederick Reines and Clyde Cowan at Los Alamos started planning experiments. In 1956, using the Savannah River reactor as a neutron source, Reines and Cowan found signals that were considered signs of neutrino–proton reactions (Cowan et al., 1956). Reines shared with Martin Perl the 1995 Nobel Prize for physics (Cowan had died earlier). In his Nobel Prize acceptance speech, thoughtfully entitled, "The neutrino: From poltergeist to particle", Reines referred to the original idea of Pauli in the following terms:

> The neutrino of Wolfgang Pauli was postulated in order to account for an apparent loss of energy-momentum in the process of nuclear beta decay. In his famous 1930 letter to the Tübingen congress, he stated: "I admit that my expedient may seem rather improbable from the first, because if neutrons[2] existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained . . . We should therefore be seriously discussing every path to salvation." *(Reines, 1997, p. 203)*

In June 1956, Reines and Cowan sent a telegram to the man who started it all (Pauli) informing him that they had definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Pauli's response was prophetic indeed and shows yet another facet of 'science in the making,' "Everything comes to him who knows how to wait, Pauli" (Reproduced in Reines, 1997, p. 215).

According to Hanson (1958), "The neutrino idea, like those of other atomic particles, is a *retroductive conceptual construction* out of what we observe in the large" (p. 124, emphasis added). Considering the immense efforts required to detect the neutrino, Kuhn (1970) concluded: "no experiment can be conceived without some sort of theory, the scientist in crisis will constantly try to generate speculative theories that, if successful, may disclose the road to a new paradigm" (p. 87).

In contrast to the traditional textbook science, these two episodes from 'science in the making' (Neptune and neutrino) clearly show that scientists generally resist the refutation of a theory by putting up alternatives and that besides the experimental apparatus a scientist is almost always accompanied by his presuppositions that provide guidance in the face of difficulties.

Schwab versus Hanson: From Structure of a Discipline to Structure of Scientific Knowledge

In this section I plan to contrast the views of educational philosopher Joseph Schwab with those of physicist-philosopher Norwood Russell Hanson. This is based on an exchange between the two at the Fifth Annual Phi Delta Kappa Symposium on Educational Research, held at the College of Education, University of Illinois, 1964. Schwab was then Professor of Education, Graduate School of Education, University of Chicago and Hanson was Professor of Philosophy at Yale University. There were other participants at the Symposium, familiar to science educators, such as: David Ausubel, Professor of Educational Psychology, University of Illinois; Carl Bereiter, Assistant Professor of Educational Psychology, University of Illinois; Egon Guba, Director, Bureau of Educational Research and Service, Ohio State University; Nathaniel Gage, Professor of Educational Psychology, Stanford University. By any standard, this was a very select group of considerable interest to research in science education and the issues discussed bear witness to the intellectual acumen of the participants.

Schwab (1962, 1974) is well known for his *Structure of a Discipline*, and Hanson (1958) for his *Patterns of Discovery*. In his lecture at the Symposium, Hanson emphasized the difference between the Binomial theorem and a description of physical phenomena in binomial form. In contrast to mathematics, subject matter in physics is not exclusively determined by the postulates and principles of inference. After providing various examples, Hanson (1964) concluded: "*No statement of pure mathematics can be presumed necessarily true when adapted to physical inquiry*" (p. 152, original italics). For example, it is not a mathematical truth that a body will either remain at rest or else move uniformly and rectilinearly to infinity, in the absence of impressed forces. Although this is a standard assumption in kinematics, Hanson wanted students to know that Aristotle and two millennia of Aristotelians would have denied such a claim. After Hanson (1964) finished his lecture, the following exchange took place with Schwab (in order to avoid lengthy sequences, some of the responses have been shortened):

Schwab: . . . an idea developed by Einstein that the greatest mistake that we make about physics is to suppose that it is an "inductive" science. Einstein and Whewell . . . suggest that physics, quite the contrary, is the imaginative invention of an essentially mathematical construction adequate to subsume the data which one is concerned to organize and account for (p. 164).

Hanson: What you say is false (p. 165).

Schwab: Wait a minute. And consequently when the empirical test is made, as you are insisting that it must be made, it is made not of an isolated proposition alone but on the entire corpus (p. 165).

Hanson: That's alright (p. 165).

Schwab: . . . insofar as the whole big corpus of theory can be treated algorithmically then there is a funny way in which physics and mathematics do mix . . . (p. 165).

Hanson: That's what you are suggesting and that's what I am denying . . . even the most "transparent" principle, like the Principle of Conservation of Energy . . . remain empirically vulnerable claims . . . semantically, the pure physics and the pure mathematics are on opposite sides of the logical ravine (pp. 165–166).

Schwab: Nobody in his right mind could argue against your thesis as to which side of the ravine physics is on (p. 166).

Hanson: Then I don't understand what *you* are arguing about (p. 166, original italics).

Schwab: I am not arguing . . . For example, you know very well that one of the particles that [Wolfgang] Pauli invented was invented precisely for the convenience of preserving one of the conservation laws . . . (p. 166).

Hanson: You are really answering my question for me, because it was the nature of that "invention" of the *neutrino* (in 1929 and 1930), an invention generated solely in order to save the conservation principle, which threw a shadow of dubiety on that particular discovery. It wasn't until the empirical work of Cowan and Reines in 1956 and 1957 (at Savannah River) that the neutrino became fully respectable; *there* was an observable effect that showed the physicist not only to be *inventing* entities to save a theory, but also to be discovering empirical evidence for this invention (p. 166, original italics).

Schwab: I agree (p. 166).

Hanson: [Anderson told me]: "I don't believe there is any such thing. All they (Cowan and Reines) show are some numbers, and not all of the numbers. I can just barely believe there is a genuine effect." . . . what Anderson was saying then was this: "If you really want me to entertain the neutrino as a physical entity capable of all the explanatory tricks the theoreticians want, then show me something, in a cloud chamber or somewhere . . . I want to see what the *difference* is that answers to the name 'neutrino.'" Now you are quite right to point out that, to theoreticians, this kind of complaint doesn't mean much—or not very much (p. 169, original italics). [Carl D. Anderson, a former student of Robert Millikan discovered the positron in 1932. Hanson met him at the High Energy Conference in Rochester in 1957, and the remark cited above was made when they were discussing the evidence for the existence of the neutrino].

Schwab: . . . for every ten Andersons there is one Fermi, who said it would be nice if neutrinos were verified in the way which neutrons, protons, and electrons were, but I think it would be helpful to adopt it now (p. 171).

Hanson: Well, that is a nice statement about *you*, Joe . . . All I am trying to call attention to is what you are obscuring (and in so doing you are being "nasty, brutish, and short"). If one stresses what you are stressing, namely, that in physics you . . . (p. 171, original italics).

Schwab: Well, you . . . (p. 171).

Hanson: If I may just finish, *please*. If one stresses what you have been stressing . . . one fails to perceive the fundamental logical difference between every single proposition of physical theory and every single proposition in a purely mathematical algorithm (pp. 171–172, original italics).

At first sight it seems that the issues being discussed by Hanson and Schwab are of minor importance and not of direct relevance to science education. However, I will now elaborate and show that despite the similarities of views the issues being discussed are of fundamental importance for 'science in the making,' understanding the NOS, and teaching science. Furthermore, it is important to note that despite a similar epistemological stance, both Hanson and Schwab make a passionate and rather obdurate defense of their respective positions, leading to some tense moments in the debate. This also shows that understanding the NOS is a difficult enterprise and similar debates have also been observed at science education conferences (for details, see Niaz, 2008a, pp. 135–136).

It seems that the difference between the epistemological positions of Hanson and Schwab can be summarized in the following terms: For Hanson, despite the similarities mathematical propositions are axioms which cannot be adapted in the context of physical science. On the contrary, Schwab would suggest that propositions and their meaning (or premises) do not directly refer to empirical facts, and thus there is something strangely mathematical about physics. Schwab (1964) presents his perspective of scientific knowledge in cogent terms:

> In general, then, enquiry has its origin in a *conceptual structure*. This structure determines what *questions* we shall ask in our enquiry; the questions determine what data we wish; our *wishes* in this respect determine what *experiments* we perform. Further, the *data*, once assembled, are given their *meaning and interpretation* in the light of the conception which initiated the enquiry. *(p. 9, emphasis added)*

Indeed, this constitutes an outline of a research methodology based on: conceptual structure → questions → wishes (i.e., presuppositions) → experiments → data → understanding based on meaning and interpretation. These are important issues for understanding 'science in the making' within an HPS perspective.

At this stage it would be interesting to see how Duhem (1914) an important philosopher of science would view this dilemma: "What the physicist states as the result of an experiment is not the recital of observed facts, but the interpretation and the transposing of these facts into the *ideal, abstract, symbolic world* created by the theories he regards as established" (p. 159, italics added). In the case of a clash between the two (empirical facts and theory), Duhem suggested upholding the experimental facts and considered the theory to be a "parasite," which in a way contradicted his own philosophical position. Now it is plausible to suggest that the *ideal, abstract, symbolic world* comes quite close to what Schwab referred to as propositions and their meaning. The controversy between Hanson and Schwab also reflects a contradiction similar to that of Duhem. Hanson seems to be upholding a position, quite similar to that of Duhem, that considers the experimental facts to be paramount. Schwab, on the contrary, espouses a philosophical position that comes quite close to what scientists do (based on a pluralistic model) under such circumstances and fully endorsed by Lakatos:

> In the pluralistic model the clash is not "between theories and facts" but between two high-level theories: between an *interpretative theory* to provide the facts and an *explanatory theory* to explain them; and the interpretative theory may be on quite as high a level as the explanatory theory . . . *the problem is which theory to consider as the interpretative one which provides the "hard" facts and which the explanatory one which "tentatively" explains them.* In a mono-theoretical model we regard the higher-level theory as an *explanatory theory to be judged by the "facts"* delivered from outside (by the authoritative experimentalist): in the case of a clash we reject the explanation. *(Lakatos, 1970, p. 129, original italics)*

According to Lakatos, based on a mono-theoretical model a theory can be rejected on the sole grounds of experimental evidence. 'Science in the making' (based on the pluralistic model) shows that rejection of a theory is not a simple and straightforward question of accepting or rejecting experimental evidence. On the contrary, interpretation of experimental evidence is extremely difficult, which leads to conflicts and controversies among contending groups of scientists. Within the Lakatosian framework the "hard-core" (negative heuristic) of a research program is resistant to refutation and may even be based on contradictory and inconsistent foundations (for details, see Niaz, 2011, pp. 15–16). Similarly, Giere (2006) has endorsed the pluralistic view of progress in science based on "perspectival realism" (p. 5). In contrast to "objective realism," Giere espouses a perspective according to which no theory can provide us with a complete and literally correct picture of the world.

History of science shows that scientific controversies at times can continue for decades and are generally brought to a closure by the intervention of the scientific community (e.g., Millikan's oil drop experiment, cf. Niaz, 2005a). It is precisely in this respect that the Lakatosian framework goes beyond Duhem by suggesting that scientists are guided by their presuppositions (hard-core of beliefs) and they resist any change in this *ideal*, *abstract* and *symbolic* world. Niaz (2009a, Chapter 3) has presented a detailed comparison of the philosophies of Duhem and Lakatos and concluded that scientific endeavor depends to a large degree upon the imagination and creativity of the scientists.

In this context, it is now possible to understand better the debate between Hanson and Schwab, especially with respect to the discovery of the neutrino. According to Schwab, scientific propositions (presuppositions, Holton, 1978; hard-core of beliefs, Lakatos, 1970) may be accepted even before confirming experimental evidence becomes available. Two leading physicists-historians of science would endorse a similar thesis in categorical terms: "Yet physicists had so much faith in the law of conservation of energy that they preferred to believe in an apparently unobservable particle [neutrino, suggested by Pauli] rather than abandon the law" (Holton & Brush, 2001, p. 502).

Similarly, Lawson (2010) has emphasized the role of theory-driven research for science education. 'Science in the making' provides many examples of how it is the theory (presuppositions) that decides what can be considered as data: (a) J.J. Thomson's rejection of E. Rutherford's hypothesis of compound scattering (alpha particle experiments) as he strongly believed in the uniform distribution of mass and charge in his atomic model (plum-pudding); (b) Millikan's determination of the elementary electrical charge based on his presupposition of the atomic nature of electricity; (c) Millikan's acceptance of Einstein's equation to determine Planck's constant *h* (photoelectric effect) and yet he still rejected the hypothesis of light quanta, as he strongly believed in the classical wave theory of light; (d) controversial experimental evidence of the bending of light in the 1919 eclipse experiments to support Einstein's general theory of relativity (cf. Niaz, 2009a, Chapter 9); (e) De Broglie's postulation of wave-particle duality before there was any experimental evidence. According to Schwab (1974) besides the presuppositions, scientific inquiry tends to look for patterns of change and relationships, which constitute the heuristic principles of scientific knowledge. It is precisely these heuristic principles that guide us to look for facts and what meaning to assign these facts. Various historical episodes discussed in Chapter 2, illustrate how the heuristic principles facilitate the designing of experiments.

Chapter Outlines

'Science in the Making' and Heuristic Principles in a Historical Context (Chapter 2). This chapter analyzes various episodes in the history of science based on the following framework: (1) Elaboration of a theoretical framework based on presuppositions; (2) Formulation of research questions; (3) Operationalizing heuristic principles; (4) Designing experiments; and (5) Understanding the NOS. The following episodes that constitute important examples of 'science in the making' were analyzed: (a) Dalton's determination of the law of multiple proportions in chemistry; (b) Maxwell's kinetic theory of gases; (c) Mendeleev's periodic table of chemical elements; (d) Thomson's determination of the mass to charge ratio of cathode rays; (e) Rutherford's alpha particle experiments and the

nuclear atom; (f) Bohr's model of the atom; (g) Millikan's determination of the elementary electrical charge; (h) Millikan's determination of Planck's constant *h*; and (i) Determination of wave-particle duality by de Broglie. After having shown how 'science in the making' in a historical context facilitates an understanding of the NOS, it is suggested that the next step would be to incorporate these historical episodes in the context of the science curriculum and elaborate appropriate science stories.

Students' and Teachers' Understanding of the Nature of Science (Chapter 3). This chapter reviews research on the following aspects and draws implications for science education: (a) Epistemological beliefs of students and teachers with respect to the NOS; and (b) Facilitating students' and teachers' understanding of the HPS, based on topics that are already in the science curriculum. This thematic review focuses on studies published in the period, 2004–2008 and draws upon articles in the following journals: *International Journal of Science Education* (n = 34), *Journal of Research in Science Teaching* (n = 28), and *Science Education* (n = 32). Of the 94 studies reviewed, 60 (65%) are classified in the section on epistemological beliefs. Based on the subject, treatment, and orientation of the study, the following seven categories are generated: (1) Relationship between students' and teachers' epistemological beliefs (n = 27); (2) Myth of the scientific method (n = 3); (3) Children's scientific reasoning (n = 4); (4) Scientists' views of the NOS (n = 9); (5) the NOS and the science curriculum (n = 10); (6) the NOS and students' laboratory practice (n = 6); and (7) Science exhibitions for understanding the NOS (n = 1). Thirty-four studies are classified in the section on facilitating students' and teachers' understanding of the HPS, and the following six categories are generated: (1) The role of argumentation (n = 9); (2) Explicit and reflective vs. implicit inquiry-oriented instruction (n = 11); (3) The use of NOS-enriched materials (n = 7); (4) The use of history-based instructional material (n = 3); (5) The use of technology-based historical materials (n = 2); and (6) The use of science apprenticeship programs (n = 2).

How to Introduce the Nature of Science in the Classroom (Chapter 4). The objective of this study is to facilitate chemistry teachers' understanding of the NOS and explore difficulties involved in its implementation in the classroom. The study is based on the responses of 16 in-service teachers who had registered for an 11-week course on the "Epistemology of Science Teaching," as part of their Master's degree program in education. The course is based on 13 readings drawing on the NOS, critical evaluation of the NOS, and critical evaluation of constructivism. Course activities included written reports, classroom discussions based on participants' presentations, and written exams.

The Role of Heuristic Principles in Understanding the Nature of Science (Chapter 5). Research in science education has drawn attention to the need for differentiating between experimental data and "heuristic principles" that facilitate understanding of the NOS. The objective of this study was to facilitate chemistry teachers' understanding that emphasis on experimental data leads to a "rhetoric of conclusions" and does not facilitate understanding of the NOS. The study is based on 26 in-service teachers who had registered for a 10-week course on "Investigation in the Teaching of Chemistry," as part of their Master's degree program. The course is based on 18 readings drawing on the HPS, students' alternative conceptions, and conceptual change. Course activities included written reports, classroom discussions based on participants' presentations, and written exams.

How the Views of Leon Cooper (Nobel Laureate) can Influence In-service Teachers' Understanding of the Nature of Science (Chapter 6). Research in science education has recognized the importance of the NOS for understanding science. Leon Cooper (Nobel laureate, physics, 1972), has presented a framework based on the HPS to facilitate a better appreciation of the dynamics of scientific progress. The objective of this study is to evaluate how the views of a Nobel laureate can influence in-service teachers' understanding of the NOS based on a reflective and explicit, activity-based approach. The study is based on the responses of 20 participants who had registered for an introductory course as part of their doctoral program. Besides other material, the framework developed by Cooper (Niaz, Klassen, McMillan, & Metz, 2010b) was required reading. The importance of understanding experiments (oil drop, cathode rays, alpha particles, photoelectric, etc.) within an HPS perspective was explicitly discussed in class. At the end of the course all participants were evaluated on the responses to a five-item questionnaire, based on assertions derived from Cooper's framework. Participants were required to respond by indicating if they were: (a) In agreement, (b) In partial agreement, or (c) In disagreement, and explain their response.

Martin Perl's (Nobel Laureate) Perspective on the Nature of Science and Teaching Science (Chapter 7). Martin L. Perl was the recipient of the 1995 Nobel Prize in physics for his discovery of the Tau Lepton, based on a 16-year history (1963–1979), when all experimental measurements agreed with the hypothesis that the Tau was a lepton produced by a known electromagnetic interaction. Besides this, Perl has also worked on the isolation of elementary particles with fractional electric charge, namely quarks. Based on his experience as an experimental scientist, Perl has formulated a philosophy of speculative experiments (Perl, 2004; Perl & Lee, 1997). The objective of this chapter is to present a brief account of the discovery of the Tau Lepton and work on quarks, in order to understand the NOS and then draw implications for teaching science.

Nature of science manifests itself in the different topics of the science curriculum as heuristic principles. Textbooks, by emphasizing not only the empirical nature of science but also the underlying heuristic principles, can be particularly helpful in facilitating conceptual change (Niaz, 2001a). It is plausible to suggest that 'science in the making' based on historical reconstructions can provide students and teachers with innovative teaching strategies in order to facilitate a better understanding of the nature of science (Niaz, 2011).

Notes

1 Kenneth G. Wilson was awarded the 1982 Nobel Prize in Physics for his theory of critical phenomena in connection with phase transitions. In Gooday et al. (2008), Wilson has posed an interesting question: "Does science education need the history of science?" and responded in the affirmative by suggesting that the history of science be included in the science curriculum.

2 When the neutron was discovered by Chadwick in 1932, Fermi renamed Pauli's particle the 'neutrino'.

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