INNOVATING SCIENCE TEACHER EDUCATION

A History and Philosophy of Science Perspective

MANSOOR NIAZ

ROUTLEDGE

Innovating Science Teacher Education

"This is an important study. Science teaching and the preparation of science teachers is dominated by a far too uncomplicated understanding of the nature of science. Mansoor Niaz brings a strong and clear mastery of the history and philosophy of science to bear on pressing issues in the teaching of science. He presents a valuable perspective on how we should understand the nature of science and how we can work with pre-service and in-service teachers to strengthen their appreciation."

Louis Rosenblatt, Baltimore Freedom Academy

Science does not advance by just doing experiments and collecting data. Progress in science inevitably leads to controversies and alternative interpretations of data. How teachers view the nature of scientific knowledge is crucial to their understanding of science content and how it can be taught.

This book presents an overview of the dynamics of scientific progress and its relationship to the history and philosophy of science, and then explores their methodological and educational implications and develops innovative strategies based on actual classroom practice for teaching topics such as the nature of science, conceptual change, constructivism, qualitative-quantitative research, and the role of controversies, presuppositions, speculations, hypotheses, and predictions.

In recent decades a worldwide sustained effort has been underway to introduce history and philosophy of science into the science curriculum, textbooks, and classrooms. Implementation of these reform projects requires teacher training that promotes an understanding of the nature of science and the dynamics of scientific progress. Field-tested in science education courses, the book is designed to involve readers in critically thinking about history and philosophy of science and to engage science educators in learning how to progressively introduce various aspects of "science-in-the-making" in their classrooms, to promote discussions highlighting controversial historical episodes included in the science curriculum, and to expose their students to the controversies and encourage them to support, defend, or critique the different interpretations. *Innovating Science Teacher Education* offers guidelines to go beyond traditional textbooks, curricula, and teaching methods and innovate with respect to science teacher education and classroom teaching.

Mansoor Niaz is Professor at the Chemistry Department, Universidad de Oriente, Cumaná, Venezuela.

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Mansoor Niaz

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To Magda and Sabuhi
For their love, patience and understanding

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Preface

Research in science education has recognized the importance of history and philosophy of science (HPS). Over the last two decades there has been a worldwide sustained effort to introduce HPS in the science curriculum, textbooks and the classroom. Similarly, various reform efforts in different parts of the world have recognized the importance of presenting science to the students within an HPS perspective (e.g., *Project 2061* by the American Association for the Advancement of Science, AAAS). Implementation of these reform projects requires teacher training in order to facilitate an understanding of how science develops and the dynamics of scientific progress. Consequently, in order to change the educational landscape we need to familiarize teachers with developments in HPS so that they can teach science as practiced by scientists. Research has also shown that these aspects with respect to the nature of science have generally been ignored by textbooks, classroom teachers and some curriculum developers. This book provides a comprehensive overview of the contemporary history and philosophy of science and its implications for science teacher education.

History of science shows that most of the major achievements of what we now take as the advancement or progress of scientific knowledge have been controversial due to alternative interpretations of experimental data. Scientific controversies are found throughout the history of science. While nobody would deny that science in the making has had many controversies, most science textbooks and curricula consider it as the uncontroversial rational human endeavor.

This book is based on the following epistemological guidelines: (a) it is the problem to be researched that determines the methodology to be used; (b) a historical reconstruction of a scientific theory can determine the different sources that contributed to its development; and (c) discussion of the historical reconstructions based on interactions among classroom teachers can facilitate the elaboration of new teaching strategies. These guidelines have been followed in this book while discussing the different historical episodes, which have important implications for teacher training.

Based on these considerations my book presents an overview of the dynamics of scientific progress and then develops innovative teaching strategies based on actual classroom practice. Development of the teaching strategies in turn is anchored in high school and introductory level university teachers, who were participating in graduate courses. The sequence of courses (methodology, epistemology and research) was designed with the objective of progressively introducing various aspects of "science in the making". Classroom discussions were based on highlighting controversial aspects of various historical episodes included in the science curriculum. Participating teachers were not only exposed to the controversies but also encouraged to support, defend or critique the different interpretations. Just as the historical reconstructions discussed in class provide a glimpse of "science in the making", all chapters of this book facilitate an understanding of how teachers interact to critically appraise dynamics of scientific progress. Some of the salient features of my book are:

a. Historical reconstructions presented are very different from textbook presentations.
b. Historical and philosophical discussions are not simple adjuncts to the course but rather an essential part of the curriculum.
c. Science does not advance by just doing the experiments and having the data.
d. Progress in science inevitably leads to controversies and alternative interpretations of data.
e. Teachers' epistemological outlook is crucial in order to facilitate conceptual understanding.
f. Motivation of teachers to question the conventional wisdom with respect to progress in science (as depicted in textbooks) and pursue further studies within a history and philosophy of science perspective.
g. Given the opportunity, teachers can critically scrutinize the different historical episodes and suggest ways for innovating classroom practice.
h. Teaching science as practiced by scientists is an important guideline for teacher training.

In writing this book my objective was not any particular course. This has the advantage that the book could be adopted partially for various types of courses, such as: Introduction to history and philosophy of science; Research methodology; Dynamics of scientific progress; How to introduce nature of science in the classroom. My book explicitly deals with the following aspects: (a) teacher-training courses based on the experience of in-service teachers; (b) history and philosophy of science as an essential part of the science curriculum; (c) methodological (qualitative, quantitative, mixed methods, controversies, presuppositions, speculations, hypotheses, predictions); and (d) history and philosophy of science as part of classroom practice (alternative interpretations, nature of science, ideas about science, tentative nature of scientific knowledge). The intended audience for this book is: secondary and introductory level university teachers, science teacher educators, researchers in science education, science teachers, science methods course teachers and students and graduate students.

Chapters 2–11 of this book deal with different aspects of history and philosophy of science and how it can be incorporated in the classroom, and can easily constitute a course outline. Chapter 2 contrasts the role of presuppositions, contradictions, controversies and speculations (i.e., science in the making) with

Kuhn's "normal science". Based on this, Chapter 3 provides a rationale for mixed methods (integrative) research programs in education. Alternative approaches to methodology in educational research are explored in Chapter 4. Possibility of generalization in qualitative educational research is considered in Chapter 5. Difficulties associated with qualitative research in education is the subject of Chapter 6. Ability to formulate hypotheses and predictions is treated in Chapter 7. Alternative interpretations of conceptual change based on rival theories are discussed in Chapter 8. Role of historical controversies and their application in the classroom is the subject of Chapter 9. Chapter 10 considers which ideas about science should be included in the classroom based on a historical perspective. Finally, based on constructivism, understanding tentative nature of scientific knowledge is illustrated in Chapter 11. Contents of this book can be divided into three main groups: (a) Chapters 2 and 3 primarily deal with philosophical questions; (b) Chapters 4–7 are based on methodological problems; and (c) Chapters 8–11 illustrate how history and philosophy of science can be introduced in the classroom. Based on their interests and orientation readers can select the appropriate chapters.

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This book has been in preparation for almost 20 years, in which I have interacted and received feedback from many colleagues, friends and my students. Looking back over these years, I had no idea that this work would take the form of a book. My institution, Universidad de Oriente (Venezuela), has supported most of my research activities. Juan Pascual-Leone (York University, Toronto) has been a major source of inspiration for understanding cognitive psychology and later my interest in history and philosophy of science. I have benefited immensely from discussions and criticisms at different stages from: Richard F. Kitchener (Colorado State University), Art Stinner (University of Manitoba), Stephen Klassen (University of Winnipeg), Michael R. Matthews (University of New South Wales), Stephen G. Brush (University of Maryland) and Gerald Holton (Harvard University).

I would like to thank the three reviewers who provided constructive criticisms and at the same time encouragement for completing the book. Louis Rosenblatt provided insight with respect to the tentative nature of science in situations where different interpretations are offered and views held despite seeming refutation. William Cobern (Western Michigan University) pointed out the folly of ideological decisions on research methods, namely the research questions need to drive our research methods. Chin-Chung Tsai (National Taiwan University of Science and Technology) considered the analogies between physical science experiments and social science research to be helpful for educational research.

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Chapter 1

Introduction

Most science teachers, textbooks and curricula consider progress in science to be based entirely on experiments, which provide evidence that unambiguously leads to the formulation of scientific theories. A historical reconstruction of the different topics of the science curriculum reveals that although experiments are important, interpretation of the data is even more important. In order to develop their research programs, besides the experimental data, scientists rely on their guiding assumptions (presuppositions), which inevitably leads to conflicts and controversies. Review of the literature based on textbook analyses reveals almost a complete lack of understanding of the role played by presuppositions, contradictions, controversies and speculations (Niaz, 2008a). In the early stages of all research, scientists are groping with difficulties, future of the research cannot be predicted, interpretations are uncertain and stakes are high due to competing groups (peer pressure). Furthermore, students' understanding of nature of science is quite similar to that of the textbook. The traditional science curriculum in general would seem to ignore the "how" and "why" of science in the making. Studies presented in this book suggest that the teacher, by "unfolding" the different episodes (based on historical reconstructions), can emphasize and illustrate how science actually works, namely tentative, controversial rivalries among peers and alternative interpretations of data. Consequently, innovating science teacher education is an important part of the research agenda.

According to Gage (2009), as compared to other areas in education, research on teaching has been neglected and suggests the following topics for research: need for a theory, evolution of a paradigm for the study of teaching, conception of the process of teaching, conception of the content of teaching, conception of students' cognitive capabilities and motivations, conception of classroom management and the integration of these conceptions. Borko, Liston and Whitcomb (2007) have also recognized that teacher education is relatively a new field of study. Furthermore, these authors have emphasized the importance of research in teacher education and suggested:

> Several sound research genres are available to the teacher education research community, each genre better suited for some questions than others. *The researcher's first and most essential role is to pose questions of practical and*

> *theoretical significance*. Researchers then should evaluate which genre or combination of genres best fits the question(s) and the resources available to conduct a well-designed study.
>
> (p. 9, emphasis added)

This is sound advice, in view of the fact that most methodology courses suggest that researchers should first select the genre of research (qualitative, quantitative, mixed, etc.) and then the question to be investigated. A leitmotiv of this book is that it is the problem to be researched that determines the methodology to be used. It seems that after the paradigm wars (Gage, 1989; Phillips, 1983), the research community has learned that we cannot adopt the research methodology a priori but rather let the problem situation provide the rationale and guidelines. This is a major step in going beyond the paradigm wars (Saloman, 1991).

The Arizona Collaborative for Excellence in the Preparation of Teachers (ACEPT) Program is one of several reform efforts supported by the National Science Foundation in the USA. The primary ACEPT reform mechanism has been month-long summer workshops in which university and community college science and mathematics faculty learn about instructional reforms and then attempt to apply them in their courses. Adamson et al. (2003) studied whether enrollment of pre-service teachers in one or more of these ACEPT-reformed undergraduate courses is linked to the way they teach after they graduate and become in-service teachers and concluded: "These results support the hypothesis that teachers teach as they have been taught. Furthermore, it appears that instructional reform in teacher preparation programs including both methods and major's courses can improve secondary school student achievement" (pp. 939–940). If "teachers teach as they have been taught" then innovating teacher training programs is all the more important. Teachers not only contribute to the development of individuals and societies but also attain self-realization through teaching (Shim, 2008).

In a recent survey conducted among members of the National Association for Research in Science Teaching (NARST) to determine the importance of issues faced by the science education community, the two top priorities were enhancing in-service teacher education and improving pre-service teacher education (cf. Czerniak, 2009). Given the presence of NARST members both in the USA and many other countries, it seems that teacher training constitutes an important part of the science education research agenda.

Historians and philosophers of science have devoted a considerable amount of work toward understanding the dynamics of scientific progress and what constitutes nature of science, NOS (Giere, 2006; Niaz, 2009a). In contrast, most students and teachers in most parts of the world frequently believe that science is a collection of facts and that the best way to learn science is to memorize those facts (Linn, Songer & Lewis, 1991). Millar (1989) has cautioned against perceiving nature of science as an empiricist epistemology, for the following reasons: (a) pedagogical: teaching science becomes a business of rote memorization of standard facts, laws, theories, methods and problem-solving procedures; and (b) epistemological: science is viewed as infallible and a body of absolute facts or received knowledge. The degree to which students' conceptions of NOS are influenced by their teachers and textbooks is the subject of considerable research. According to Lederman (1992), such influence is mediated by a complex set of factors, such as curriculum constraints, administrative policies and teachers' conceptualization of learning. Given the complexity and multifaceted nature of the issues involved and a running controversy among philosophers of science themselves, implementation of NOS in the classroom has also been difficult. Despite the controversy a certain degree of consensus has been achieved within the science education community and nature of science can be characterized, among others, by the following aspects (Abd-El-Khalick, 2004; Lederman, 2004; McComas et al., 1998; Niaz, 2001a, 2008b; Osborne et al., 2003; Scharmann & Smith, 2001; Smith & Scharmann, 1999):

1. Scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, rational arguments and skepticism.
2. Observations are theory-laden.
3. Science is tentative/fallible.
4. There is no one way to do science and hence no universal, recipe-like, step-by-step scientific method can be followed.
5. Laws and theories serve different roles in science and hence theories do not become laws even with additional evidence.
6. Scientific progress is characterized by competition among rival theories.
7. Different scientists can interpret the same experimental data in more than one way.
8. Development of scientific theories at times is based on inconsistent foundations.
9. Scientists require accurate record keeping, peer review and replicability.
10. Scientists are creative and often resort to imagination and speculation.
11. Scientific ideas are affected by their social and historical milieu.

A review of the literature shows that most teachers in many parts of the world lack an adequate understanding of some or all of the different NOS aspects outlined above (Akerson et al., 2006; Bell et al., 2001; Blanco & Niaz, 1997; Clough, 2006; Dogan & Abd-El-Khalick, 2008; Lederman, 1992; Mellado et al., 2006; Pomeroy, 1993; Tsai, 2002). This should be no surprise to anyone who has analyzed science curricula and textbooks, which have a pronounced stance toward an entirely empiricist and positivist epistemology. Tsai (2006) has argued cogently for including the various aspects of NOS for both pre-service and in-service teacher training:

> Scientific knowledge should be regarded as an invented reality, which is also constructed through the use of agreed-upon paradigms, acceptable form of evidence, social negotiations in reaching conclusions, and technological, contextual and cultural impacts are recognized by participating scientists. These views are very different from traditionally *empiricist* perspectives. The empiricist position assumes that scientific knowledge is a discovery of an

> objective reality external to ourselves and discovered by observing, experimenting or application of a universal scientific method.
>
> (pp. 363–364, original italics, underline added)

Let us now compare this with what Steven Weinberg (2001), Nobel Laureate in physics, has to say about objective reality and truth in science: "What drives us onward in the work of science is precisely the sense that there are *truths out there to be discovered*, truths that once discovered will form a permanent part of human knowledge" (p. 126, emphasis added). No wonder science curricula and textbooks in most parts of the world follow a similar epistemology. Giere (2006) has characterized such philosophical positions as "objectivist realism" (p. 5), and explained cogently:

> Weinberg should not need reminding that, at the end of the nineteenth century, physicists were as justified as they could possibly be in thinking that classical mechanics was objectively true. That confidence was shattered by the eventual success of relativity theory and quantum mechanics a generation later.
>
> (p. 118)

This leads to yet another interesting issue: do all Nobel Laureates in physics follow "objectivist realism"? The following statement from Leon Cooper, another Nobel Laureate in physics, can provide science teachers a better insight with respect to the dynamics of scientific progress:

> Observations can have varying interpretations, but this does not undermine the objective nature of science … It's somewhat ironic that what we like to call the meaning of a theory, its interpretation, is what changes. Think, for example, of the very different views of the world provided by quantum theory, general relativity and Newtonian theory.
>
> (p. 47, reproduced in Niaz, Klassen, McMillan & Metz, 2010a)

As a methodological guideline (important for teacher training), Giere (2006) suggests that only a historical examination of a scientific theory can determine the different sources that contributed to its development (p. 6). Similarly, Phillips (2005a) has critiqued educational research for not providing real examples and concluded that philosophy of educational research is roughly at the stage that much philosophy of science was six decades ago (Phillips is referring to the in-depth historical studies starting in the 1950s by contemporary philosophers of science, such as Popper, Kuhn, Lakatos, Cartwright and Galison). In contrast to Giere's (2006) "objectivist realism", Cobern and Loving (2008) have espoused an "epistemological realism" with the following caveat, "science is imperfect, incomplete and fallible; and is not the only source of knowledge that we as humans find of value" (p. 443). These critiques and reflections have served as a guideline in the elaboration of the different historical episodes in this book (especially Chapter 3) and their implications for teacher training.

Kenneth Wilson, another Nobel Laureate in physics, has argued forcefully as to how the "perpetual flux" in the history of science can cultivate students' expectations of how they might contribute to future changes in scientific innovation:

> The key role of history here is characterizing the complexities of how science *changes*. So many science textbooks unhelpfully—and above all inaccurately—cultivate a rather static image of scientific disciplines, as if they were completed with comprehensive certainty. It is perhaps not difficult to understand how this gross oversimplification might arise as the result of a pedagogical need to "tidy up" the presentation of science to meet the needs and capacities of students. But faced with the textbook spectacle of such an apparently unalterable monolith, is it any wonder that students can have difficulty conceiving how they might ever contribute to science?
>
> (Gooday, Lynch, Wilson & Barsky, 2008, p. 326, original italics)

Wilson and Barsky (1998) have provided the lead in integrated historical teaching in order to enable students to understand what science is and how it is conducted. They have suggested that in order for these reform efforts to be successful, teacher preparation is a critical issue.

Slater (2008) has raised a provocative question for science teacher education: how to justify teaching false science? This, in turn, is based on the premise that we teach false science (e.g., Newtonian mechanics, Thomson, Rutherford and Bohr models of the atom). As a possible solution to the dilemma, Slater suggests that "the best way of teaching false science is by teaching it *as false*, but *illustratively*—incorporating a critical historical perspective into the science curriculum" (p. 541, original italics). This clearly shows the need for incorporating a history and philosophy of science perspective in the science curriculum, in order to facilitate a better understanding of the dynamics of scientific progress. In other words, "false science" can illustrate to students and teachers how understanding of experimental data in the history of science led to controversies and alternative interpretations.

With this background it would help to better understand the considerable amount of work that has been done to teach NOS in the classroom (Abd-El-Khalick & Akerson, 2004, 2007; Bianchini & Colburn, 2000; Ford & Wargo, 2007; Irwin, 2000; Khishfe & Lederman, 2006; Lin & Chen, 2002; Niaz et al., 2002; Southerland et al., 2006; Sowell et al., 2007; Von Aufschnaiter et al., 2008; Wong et al., 2008). Nevertheless, the relationship between teachers' conceptions of NOS and their classroom practice is more complex than generally appreciated. Abd-El-Khalick and Lederman (2000b) have attributed this to various factors, such as: pressure to cover content, classroom management and organizational principles, concern for student abilities and motivation, institutional constraints, teaching experience and difficulties in understanding the philosophical underpinnings of nature of science. Concern for covering content is counterproductive if we want to cultivate students' interest and motivation with respect to what is science and how it progresses, and at the same time foster a natural curiosity about the world around us. Cobern et al. (1999) have argued cogently with respect to how students' understanding of nature of science can be "successful only to the extent that science finds a niche in the cognitive and cultural milieu of students" (p. 541).

Despite the difficulties, research in science education has continued to work on the development and implementation of courses/materials both at the undergraduate and high school levels, in order to facilitate students' and teachers' understanding of NOS (Abd-El-Khalick, 2005; Abd-El-Khalick, Bell & Lederman, 1998; Niaz, 2009b; Pocoví, 2007). At this stage it would be interesting to provide greater insight into how teachers can acquire a deeper understanding of the nature of science and how progress in science is a complex process. Sadler et al. (2004) have argued cogently that science operates under the implicit assumption that scientific knowledge develops, builds upon itself and changes over time, namely, its tentative nature. Furthermore, scientists would not devote their lives to the pursuit of knowledge if they had no chance of adding to or changing prevailing paradigms. One of the participating teachers in a study designed to facilitate greater understanding of NOS provided the following informed view with respect to how observations are theory-laden:

> Science is not as objective as people would like to believe. When presented with evidence, people interpret it differently. The scientists involved in the debate about extinction of dinosaurs each came from different paradigms. They interpret their evidence according to their own paradigm.
>
> (Reproduced in Abd-El-Khalick, 2005, p. 29)

A critical reader may point out that such thinking may lead the teachers to consider decisions in the construction of scientific knowledge as arbitrary. However, this is not the intention. The important point is to understand that objectivity by itself does not help to take decisions, but rather it is the decision-making process (controversy, conflicts and alternative interpretations of data) that provides an objective status to the scientific enterprise. Campbell (1988a), a methodologist, has expressed this in succinct terms:

> [T]he objectivity of physical science does *not* come from the fact that single experiments are done by reputable scientists according to scientific standards. It comes instead from a social process which can be called competitive cross-validation … and from the fact that there are many independent decision makers capable of rerunning an experiment, at least in a theoretically essential form. The resulting dependability of reports … comes from a social process rather than from dependence upon the honesty and competence of any single experimenter.
>
> (pp. 302–303, original italics)

A major difficulty in implementing NOS is the expectation that students will come to understand it by "doing science" (Lederman, 2004, p. 315). This is like assuming that students would come to understand photosynthesis just by watching a plant grow. In order to facilitate understanding of NOS teachers need to go beyond the traditional curriculum and emphasize the difficulties faced by the scientists and how interpretation of data is always problematic, leading to controversies among contending groups of researchers. Next, examples are provided of how "doing science" is not a sufficient condition for understanding science.

J.J. Thomson (1897) is generally credited to have "discovered" the electron while doing experiments with cathode rays. Determination of the mass-to-charge (*m/e*) ratio of the cathode rays can be considered the most important experimental contribution of Thomson. Yet, he was neither the first to do so nor the only experimental physicist. Kaufmann and Wiechert also determined the *m/e* of cathode rays in the same year and their values agreed with each other (for details, see Niaz, 1998). If we demonstrate this experiment in the classroom or students handle the equipment themselves (i.e., doing science), it may be useful, and this is good educational practice. However, by emphasizing that "science is empirical" (doing experiments) we shall be denying students an important aspect of the nature of science, namely what made Thomson's work different from that of Kaufmann and Wiechert. Falconer (1987) has explained cogently how both Kaufmann and Wiechert lacked a theoretical framework (heuristic principle) to understand the data. In contrast, Thomson had a heuristic principle before doing the experiments, namely cathode rays could be considered as ions (if *m/e* ratio was not constant) or universal charged particles (if *m/e* ratio was constant). Indeed, most general chemistry and physics textbooks emphasize the experimental details (doing science) and ignore Thomson's heuristic principle for interpreting and understanding the data (for details, see Niaz, 1998; Rodríguez & Niaz, 2004a).

Soon after Geiger and Marsden (1909) published their results (working under E. Rutherford's supervision), Thomson and colleagues also started working on the scattering of alpha particles in their laboratory (again, doing the experiment in the classroom can help). Although experimental data from both laboratories were similar, interpretations of Thomson and Rutherford were entirely different. Thomson propounded the hypothesis of *compound scattering*, according to which a large-angle deflection of an alpha particle resulted from successive collisions between the alpha particles and the positive charges distributed throughout the atom. Rutherford (1911), in contrast, propounded the hypothesis of *single scattering*, according to which a large-angle deflection resulted from a single collision between the alpha particle and the massive positive charge in the nucleus. The rivalry led to a bitter dispute between the proponents of the two hypotheses (for details, see Niaz, 1998; Wilson, 1983). At one stage the controversy became so bitter that Rutherford charged that a colleague of Thomson had "fudged" the data. Once again, most chemistry and physics textbooks ignore the difficulties involved in understanding the data and the ensuing controversy (cf. Niaz, 1998; Rodríguez & Niaz, 2004a).

History of science shows how R.A. Millikan (1868–1953) and F. Ehrenhaft (1879–1952) obtained very similar experimental observations (oil drop experiment), and yet their theoretical frameworks led them to postulate the elementary electrical charge (electrons) and fractional charges (sub-electrons), respectively. The Millikan–Ehrenhaft controversy lasted for many years (1910–1923) and was discussed by leading scientists. The problematic nature of Millikan's interpretation was revealed many years later when Holton (1978a, 1978b) consulted his handwritten notebooks in CALTECH. The oil drop experiment is still used in undergraduate physics labs and continues to be problematic for students (cf. Klassen, 2009). Not surprisingly, both general chemistry and physics textbooks do present the experiment in considerable detail, and still completely ignore the Millikan–Ehrenhaft controversy (Niaz, 2000a; Rodríguez & Niaz, 2004b).

Experiments related to the photoelectric effect played a crucial role in the construction of the modern atomic theory and form an important part of the science curriculum. Once again, Robert Millikan provided the first experimental evidence for Einstein's photoelectric equation. Interestingly, however, in the same publication (Millikan, 1916), he recognized the validity of Einstein's equation and simultaneously questioned the underlying hypothesis of lightquanta put forward by Einstein. This may sound incredible to any student who has not been exposed to history and philosophy of science. Philosophers of science refer to this as underdetermination of scientific theories by experimental evidence, namely no amount of experimental evidence can provide conclusive proof for a theory (for details, cf. Niaz, 2009a). A recent study has revealed an almost complete lack of the historical perspective (essential for conceptual understanding) in presenting the photoelectric effect in general physics textbooks (cf. Niaz, Klassen, McMillan & Metz, 2010b). These authors reported that a great majority of the textbooks considered that Millikan had provided experimental evidence for Einstein's hypothesis of lightquanta, contrary to what he himself had claimed.

These examples provide a clear illustration of the dilemma involved in "doing science" and understanding science, as teachers in most parts of the world invariably emphasize the former, that is, lab activities, and thus do not arouse students' curiosity with respect to "science in the making". Interestingly, Tsai (2003) has investigated laboratory learning environments and found that teachers generally held an empiricist epistemology and showed higher preferences for better equipment than did their students. Cathode ray experiments, scattering of alpha particle experiments, photoelectric effect and the oil drop experiments are considered to be the foundation of modern science (early 20th century) and are included in science curricula and textbooks both at the upper secondary and university freshman level, in almost all parts of the world (Chapters 2 and 3 provide more details of these and other experiments). However, very rarely are students provided an insight into what the scientists were discussing/arguing with their peers while the experiments were being conducted. In other words, scientific theories require a considerable amount of ingenuity, creativity and "competitive cross-validation" in order to convince the scientific community. A major objective of this book is to provide guidelines and a framework for including these historical episodes in the upper secondary and university freshman classroom practice (see Chapters 8, 9, 10 and 11). In order to facilitate understanding, a brief overview of the different chapters of this book is presented next.

Role of presuppositions, contradictions, controversies and speculations versus Kuhn's normal science. Kuhn (1970) considered textbooks to be good "pedagogical vehicles" for the perpetuation of "normal science" (Chapter 2).

Collins (2000) has pointed out a fundamental contradiction with respect to what science could achieve (discover and create new knowledge) and how we teach science (dogmatic and authoritarian). Despite the reform efforts (*Project 2061*, *Beyond 2000*), students (secondary and university) still have naive views about the nature of science in which experimental data unambiguously lead to the formulation of laws and theories. Review of the literature based on textbook analyses shows an almost complete lack of understanding of the role played by presuppositions, contradictions, controversies and speculations in scientific progress. Kuhn's advice based on "normal science" would seem to suggest that the science curriculum need not appeal to the imagination and creativity of the students. It is not my intention to suggest that Kuhn has promoted the inclusion of "normal science" in science textbooks. The teacher by "unfolding" the different episodes (based on historical reconstructions) can emphasize and illustrate how science actually works (tentative, controversial, rivalries, alternative interpretations of the same data), and this will show to the students that they need to go beyond "normal science" as presented in their textbooks.

A rationale for mixed methods (integrative) research programs in education. Recent research shows that research programs (quantitative, qualitative and mixed) in education are not displaced (as suggested by Kuhn) but rather lead to integration. The objective of Chapter 3 is to present a rationale for mixed methods (integrative) research programs based on contemporary philosophy of science (Lakatos, Giere, Cartwright, Holton, Laudan). This historical reconstruction of episodes from physical science (spanning a period of almost 300 years, from the 17th to the 20th century) does not agree with the positivist image of science. Quantitative data (empirical evidence), by itself, does not facilitate progress (despite widespread belief to the contrary), neither in the physical sciences nor in the social sciences (education). A historical reconstruction shows that both Piaget and Pascual-Leone's research programs in cognitive psychology follow the Galilean idealization quite closely, similar to the research programs of Newton, Mendeleev, Einstein, Thomson, Rutherford, Millikan and Perl in the physical sciences. This relationship does not imply that researchers in education have to emulate research in the physical sciences. A major argument in favor of mixed methods (integrative) research programs is that it provides a rationale for hypotheses, theories, guiding assumptions and presuppositions to compete and provide alternatives. Similar to the physical sciences, this proliferation of hypotheses leads to controversies and rivalries, and thus facilitates the decision-making process of the scientific community.

Exploring alternative approaches to methodology in educational research. The objective of Chapter 4 is to provide in-service teachers an opportunity to familiarize themselves with the controversial nature of progress in science (growth of knowledge) and its implications for research methodology in education. The study is based on 41 participants who had registered for a 9-week course on Methodology of Investigation in Education, as part of their Master's degree program. The course is based on 20 readings drawing on a history and philosophy of science perspective (positivism, constructivism, Popper, Kuhn, Lakatos) and its implications for educational research (Campbell, Erickson). Course activities included written reports, classroom discussions based on participants' presentations and written exams.

Can findings of qualitative research in education be generalized? Most qualitative researchers do not recommend generalization from qualitative studies, as this research is not based on random samples and statistical controls. The objective of Chapter 5 is to explore the degree to which in-service teachers understand the controversial aspects of generalization in both qualitative and quantitative educational research and as to how this can facilitate problems faced by the teachers in the classroom. The study is based on 83 participants who had registered for a 10-week course on Methodology of Investigation in Education, as part of their Master's degree program. The course is based on 11 readings drawing on a philosophy of science perspective (positivism, constructivism, Popper, Kuhn, Lakatos). Course activities included written reports, classroom discussions based on participants' presentations and written exams.

Qualitative methodology and its pitfalls in educational research. There is considerable controversy in educational research with respect to the use of qualitative and quantitative data and as to what constitutes scientific research. The objective of Chapter 6 is to explore the degree to which in-service teachers understand the difference between qualitative/quantitative data and methods, validity/authenticity, generalization and how these can be used to solve problems faced by the teachers. The study is based on 84 participants who had registered for a 10-week course on Methodology of Investigation in Education, as part of their Master's degree program. The course is based on 11 readings drawing on a history and philosophy of science perspective (positivism, constructivism, Popper, Kuhn, Lakatos). Course activities included written reports, classroom discussions based on participants' presentations and written exams.

Did Columbus hypothesize or predict? Facilitating teachers' understanding of hypotheses and predictions. A review of the literature in science education shows that most students have difficulties in hypothetico-deductive reasoning. The ability to elaborate and differentiate between observations, hypotheses and predictions is important and need not necessarily be considered as part of the scientific method. Most philosophers of science would question the existence of a scientific method as a series of specifiable procedures that constitute an algorithm (Cartwright, 1999; Giere, 1999; Lakatos, 1970; Polanyi, 1964). The objective of Chapter 7 is to investigate high school and freshman university teachers' ability to understand the difference between *hypotheses* and *predictions* in the everyday context of Columbus' discovery of America. Eighty-three high school and introductory level university teachers enrolled in a Methodology course were asked to elaborate and explain a prediction and a hypothesis based on Columbus' discovery. As a follow up, a study was designed to facilitate in-service high school and university teachers' understanding of the difference between the terms *hypothesis* and *prediction.* The context for understanding these terms was Columbus' discovery of America (same as in the previous study). Control-group teachers ($n = 94$) were evaluated before the discussion of these terms, whereas Experimental group teachers ($n = 102$) were evaluated after these terms had been fully discussed and elaborated in class.

Facilitating teachers' understanding of alternative interpretations of conceptual change. Historians and philosophers of science have recognized the importance of controversies in the progress of science. The objective of Chapter 8 is to facilitate in-service chemistry teachers' understanding of conceptual change based on alternative philosophical interpretations (controversies). Selected controversies formed part of the chemistry curriculum both at secondary and university freshman level. The study is based on 17 in-service teachers who had registered for an 11-week course on Investigation in the Teaching of Chemistry as part of their Master's degree program. The course is based on 17 readings drawing on a history and philosophy of science perspective with special reference to controversial episodes. Course activities included written reports, classroom discussions based on participants' presentations and written exams. In this study most of the teachers went through an experience that involved inconsistencies, conflicts, contradictions and finally some degree of conceptual change. A few of the participants, however, resisted any change, but still raised important issues with respect to conceptual change.

Progressive transitions in teachers' understanding of nature of science based on historical controversies. The objective of Chapter 9 is to facilitate progressive transitions in chemistry teachers' understanding of NOS in the context of historical controversies. Selected controversies referred to episodes that form part of the chemistry curriculum both at secondary and university freshman level. The study is based on 17 in-service teachers who had registered for an 11-week course on Investigation in the Teaching of Chemistry as part of their Master's degree program. The course is based on 17 readings drawing on a history and philosophy of science perspective with special reference to controversial episodes in the chemistry curriculum. Course activities included written reports, classroom discussions based on participants' presentations and written exams. The opportunity to reflect, discuss and participate in a series of course activities based on controversies can enhance teachers' understanding of NOS.

What "ideas-about-science" should be taught in school science? The objective of Chapter 10 is to facilitate in-service chemistry teachers' understanding of nature of science and what "ideas-about-science" can be included in the classroom. The study is based on 17 in-service teachers who had registered for an 11-week course on Epistemology of Science Teaching as part of their Master's degree program. The course is based on 17 readings drawing on NOS and its critical evaluation. Course activities included written reports, classroom discussions based on participants' presentations and written exams. This course provided participant teachers an opportunity to familiarize themselves with research on what "ideas-about-science" can be taught in the classroom and how critical appraisal of the literature is necessary in order to go beyond our present understanding of the issues.

Whither constructivism? Understanding the tentative nature of scientific knowledge. Constructivism in science education has been the subject of considerable debate in the science education literature. The purpose of Chapter 11 is to facilitate chemistry teachers' understanding that the tentative nature of scientific knowledge leads to the coexistence of rivalries among different forms of constructivism in science education. The study is based on 17 in-service teachers who had registered for an 11-week course on Epistemology of Science Teaching as part of their Master's degree program. The course is based on 17 readings drawing on NOS and a critical evaluation of constructivism. Course activities included written reports, classroom discussions based on participants' presentations and written exams.

At this stage I would like to introduce some basic ideas that may be of help, especially to students who may not be familiar with recent developments in history and philosophy of science.

Positivism

It would be helpful to have a historical perspective with respect to the various forms of positivism (Phillips, 1994a). History of science shows that positivism was the dominant philosophy from about the end of the 19th century to about the middle of the 20th century. Positivism has many faces and philosophers tend to characterize it in different ways: (a) *classic positivism* can be traced to Comte (1798–1857), who emphasized that science focuses upon observation and hence scientific knowledge consisted only in the description of observed phenomena and not inferred theoretical entities; (b) *logical positivism* associated with the Vienna Circle which was very active during the 1930s and introduced the Verifiability Principle, according to which something is meaningful if and only if it is verifiable empirically, or, in other words, "if it can't be seen or measured, it is not meaningful to talk about"; (c) *behaviorism* for their hostility to abstract theorizing and metaphysics; and (d) *empiricism* which again emphasizes that our knowledge is wholly or partly based on experience through the senses and introspection. According to Phillips (1983), although logical positivism is a type of empiricism, not all varieties of empiricism are positivistic.

The importance of having positivist or more adequate epistemological views is important for teacher training. For example, Tsai (2007) has explored the relationship between middle school physical science teachers' (Taiwan) epistemological views, teaching beliefs, instructional practices and students' epistemological views. Findings suggested adequate coherence between teachers' epistemological views and teaching beliefs as well as instructional practices. Teachers with relatively positivist-aligned views tended to draw attention to students' science scores in tests and allocate more instructional time on teacher-directed lectures and in-class examinations, thus implying more passive or rote learning. In contrast, teachers with constructivist-oriented views tended to focus on student understanding and application of scientific concepts, by devoting more time to inquiry activities and interactive discussions. This clearly shows that teachers with positivist views tend to encourage and foster more traditional teaching practices based on algorithmic learning.

Similarly, logical positivism has also been the subject of study with special reference to the science curriculum. According to Van Aalsvoort (2004), most secondary school students consider chemistry to be irrelevant. Based on a review of science education literature, the atheoretical nature of the observational language and the curriculum (based heavily on the textbooks), the author concluded that chemical education is driven by logical positivism. As a philosophy of science, logical positivism creates a divide between science and society. Based on these premises, the author hypothesized that the adoption of logical positivism causes chemistry's lack of relevance in chemical education. This hypothesis was substantiated by an analysis of the secondary school chemistry curriculum in the Netherlands. Based on these considerations, the author concluded,

> Chemical education is relevant from a social point of view to the extent that the knowledge it provides is applicable to solve society's problems. Yet, due to the hierarchical relation between scientific knowledge and its applications, the former is preferred above the latter in chemical education, thereby leaving the relevance of chemical knowledge for society mostly out of sight.
> (p. 1166)

Finally, the author suggested that as an alternative to logical positivism, science educators could explore activity theory within the sociocultural approach.

Galilean Idealization

In contrast to Aristotle, who believed that a continually acting cause (i.e., force) was necessary to keep a body moving horizontally at a uniform velocity, Galileo predicted that if a perfectly round and smooth ball was rolled along a perfectly smooth horizontal endless plane there would be nothing to stop the ball (assuming no air resistance), and so it would roll on forever. Galileo, however, did not have the means to demonstrate that Aristotle was wrong, so he asked an epistemological question: what would make it (body) stop? And then went on to argue that under ideal conditions (with impediments, such as shape of the ball and the surface, controlled) a ball could roll on forever. Similarly, Galileo's discovery of the law of free fall later led to a general constructive model of falling bodies (Pascual-Leone, 1978). The law in its modern form can be represented by: $s = 1/2\ g\ t^2$ (s = distance, t = time and g = a constant). In order to "prove" his law of free fall, Galileo should have presented empirical evidence to his contemporaries by demonstrating that bodies of different weight (but of the same material) fall at the same rate. If the leaning tower of Pisa mythical experiment (cf. Segre, 1989, for recent controversy) was ever conducted, it would have shown Galileo to be wrong. According to Pascual-Leone (1978), empirical computation of the value of s as a function of the variable t, "where vacuum and other *simplifying assumptions* are not satisfied" (emphasis added, p. 28), would lead to a rejection of the law. As a direct empirical test of Galileo's ideal law was not possible, he used his inclined plane experiment to show that as the angle of incidence approximated 90° (free fall), the acceleration of objects rolling down an inclined plane increasingly approximated a constant. According to Kitchener (1993, p. 142), by extrapolation one may assume it is also true of free fall as a limiting case.

Following Galileo's method of idealization (considered to be at the heart of all modern physics by Cartwright, 1989, p. 188) scientific laws, being epistemological constructions, do not describe the behavior of actual bodies. According to Lewin (1935), for example, the law of falling bodies refers only to cases that are never realized, or only approximately realized. Only in experiment, which is under artificially constructed conditions (idealization), do cases occur which approximate the event with which the law is concerned. Furthermore, Lewin has argued that this conflict between quantification (Aristotelian) and qualitative understanding (Galilean) modes of thought constitutes a paradox of empiricism. Galileo's law of free fall, Newton's laws, gas laws they all describe the behavior of ideal bodies that are abstractions from the evidence of experience and the laws are true only when a considerable number of disturbing factors, itemized in the *ceteris paribus* clauses, are eliminated (cf. Ellis, 1991; Matthews, 1987; McMullin, 1985; Niaz, 1999a). *Ceteris paribus* clauses play an important role in scientific progress, enabling us to solve complex problems by introducing simplifying assumptions (idealization). Lakatos (1970) has endorsed this position in the following terms: "Moreover, *one can easily argue that ceteris paribus clauses are not exceptions, but the rule in science*" (p. 102, original italics). This illustrates quite cogently the research methodology of idealization utilized for studying physical laws in particular and complex problems in general.

McMullin (1985) considers the manipulation of variables (disturbing factors) as an important characteristic of Galilean idealization:

> The move from the complexity of nature to the specially contrived order of the experiment is a form of idealization. The diversity of causes found in Nature is reduced and made manageable. The influence of impediments, i.e., causal factors which affect the process under study in ways not at present of interest, is eliminated or lessened sufficiently that it may be ignored.
>
> (p. 265)

According to Rigden and Stuewer (2005), in the physical sciences, the quantitative stands in sharp contrast to the qualitative. To understand any substantive topic, qualitative understanding is important, which requires a process of internalization so that an individual can draw on his resource of words to embrace a subject meaningfully. Further details are provided by Niaz (2005a).

Kuhn's Paradigms

According to Kuhn (1970), most scientific work consists of routine resolution of problems, which constitutes "normal science". As scientists working in a field of research achieve consensus with respect to a certain theoretical framework, it leads to the formation of a paradigm, which Kuhn later referred to as a "disciplinary matrix". While solving routine problems, scientists come up with anomalies that are difficult to resolve and the accumulation of such anomalies frequently leads to the overthrow of the existing paradigm and the revolutionary period that ensues leads to the formation of a new paradigm. Kuhnian philosophy of science has been a major source of inspiration for science educators and the following aspects of his philosophy have played an important role: (a) it presupposes subjectivity as an integral part of the scientific process, once thought to be wholly objective; (b) it asserts that different paradigms are incommensurate because their core beliefs are resistant to change and hence do not permit dialogue; (c) paradigms do not merge over time, rather they displace each other after periods of chaotic upheaval or scientific revolution; (d) Kuhnian displacements are not subtle events, but are rather understood as cataclysmic clashes in which losers languish and victors flourish. Kuhn (1970) himself referred to the subject in the following terms:

> if I am right that each scientific revolution alters the historical perspective of the community that experiences it, then that change of perspective should affect the structure of postrevolutionary textbooks and research publications. One such effect a shift in the distribution of the technical literature cited in the footnotes to research reports ought to be studied as a possible index to the occurrence of revolutions.
>
> (p. ix)

Lakatos' Research Programs

In contrast to paradigms (Kuhn), Lakatos (1970) postulates the importance of research programs that are formed by the *hard-core/negative heuristic* and the *positive heuristic*. Negative heuristic is based on the theoretical framework (presuppositions) of the scientist and is not necessarily refuted by experimental evidence. Most scientists before entering the laboratory do have their presuppositions and they hope to get experimental evidence for corroboration. The positive heuristic, on the other hand, defines problems, outlines the construction of a "protective belt" of auxiliary hypotheses, foresees anomalies and suggests solutions. Auxiliary hypotheses, for example, help the scientist to protect the hard-core of their research programs. An important aspect of the Lakatos methodology is to evaluate rival research programs on a continuum between progressive and degenerate. A research program is said to be *progressing* as long as its theoretical growth anticipates its empirical growth, that is, as long as it keeps predicting novel facts with some success that is "progressive problemshifts" (Lakatos, 1971, p. 100). A research program is progressing if it frequently succeeds in converting anomalies into successes, that is, explainable by the theory. The classic example of a successful research program is Newton's gravitational theory. The negative heuristic in Newton's program is the law of gravitation and his three laws of dynamics. The positive heuristic enables the scientist to build models by ignoring the *actual* counterexamples, the available data (Lakatos, 1970, p. 135).

Application of the Lakatosian methodology to Bohr's research program as an example of how scientists progress from simple to complex models (simplifying assumptions) is quite instructive. Lakatos (1970) differentiates clearly between the negative and positive heuristic of Bohr's research program. Bohr's (1913) famous four postulates constituted the negative heuristic of his research program. Most teachers and textbooks recognize their importance and still ignore that some of these postulates were speculation for which Bohr had no warrant or experimental evidence (for further discussion, see Chapter 12).

Consequently, in the Lakatosian framework, negative heuristic of a research program is resistant to refutation and may even be based on contradictory and inconsistent foundations. Furthermore, Lakatos (1970) shows how Bohr used the methodology of idealization (i.e., simplifying assumptions) and developed the *positive heuristic* of Bohr's program by progressing from simple to complex models, that is, from a fixed proton-nucleus in a circular orbit, to elliptical orbits, to removal of restrictions (fixed nucleus and fixed plane), to inclusion of spin of the electron (this was not in discussion in 1913), and so on until the program could ultimately be extended to complicated atoms. This illustrates quite cogently the research methodology of idealization utilized for studying physical laws in particular and complex problems in general.

The study designed by Chang and Chiu (2008) to foster argumentation is a good illustration of how the Lakatosian methodology (as contrast to other philosophers of science) can be applied in the classroom. These authors asked 70 undergraduate science and non-science majors in Taiwan to provide written arguments about four socio-scientific issues. Results showed that: (a) science majors' informal arguments were significantly better than those of non-science majors; (b) science majors made significantly greater use of analogies, while non-science majors made significantly greater use of authority; (c) both groups had a harder time changing their arguments after participating in a group discussion. According to the authors, in the study of argumentation in science education, scholars have often used Toulmin's (1958) framework of data, warrant, backing, qualifiers, claims and rebuttals. In contrast, however, in their work, the authors found that Lakatos' framework is also a viable perspective, especially when warrant and backing are difficult to discern and when students' arguments are resistant to change. This framework highlights how the "hard-core" of students' arguments about socio-scientific issues does indeed seem to be protected by a "protective belt" and thus difficult to alter.

At this stage it is important to refer to whether history of science should be rated X for science education (Brush, 1974). Following Kuhn, some scholars and even science educators have argued that detailed presentations based on history of science can present an erroneous view of science that may seem to question the certainty of scientific laws and theories. Brush (2000), a former student of Kuhn, has been considered by some circles to be opposed to the introduction of history and philosophy of science in science education. On the contrary, Brush (1978) has supported the inclusion of history of science in categorical terms:

> Of course, as soon as you start to look at how chemical theories developed and how they were related to experiments, you discover that the conventional wisdom about the empirical nature of chemistry is wrong. The history of chemistry cannot be used to indoctrinate students in Baconian methods.
>
> (p. 290)

More recently, the claim that history of science corrupts the science student and thus should not be included in the curriculum has been considered by some scholars to be "superficially bizarre" (Gooday, Lynch, Wilson & Barsky, 2008).

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