Understanding the Nature of Science Through

the

Historical Development of Conceptual Models

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Submitted to the Faculty of Graduate Studies

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In Partial Fulfilment

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by

Donald J. Metz
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Understanding the Nature of Science Through the Historical Development of Conceptual Models

Abstract

Understanding the nature of science has been a common goal in science education for years and continues to hold a distinct place in the recently developed Pan-Canadian science framework. Although the nature of science is often prominent in the front end of such reform documents, the implementation of these goals is presumed to be taught implicitly with the delivery of knowledge outcomes. Research strongly indicates that most students have naive conceptions about the nature of science. Surprisingly, research also clearly shows that science teachers do not fare much better, and that when they do possess adequate understanding of the nature of science it does not significantly influence their behaviour in the classroom.

Norm Lederman (1998), one of the leading scholars in this field, describes two approaches advocated by curriculum reform documents to address the nature of science outcomes. The first approach suggests that students can achieve nature of science outcomes by "doing science", the second suggests that history of science can enhance

students' understanding of the nature of science. While Lederman advocates the use of the history of science, he argues that these approaches are not effective when used implicitly. He recommends that an explicit approach be used (planned for, taught, assessed), but so far there have been no studies which employ this technique beyond short lessons or limited case histories.

This thesis advocates an explicit approach to teaching the nature of science using the historical development of conceptual models. The research study of this thesis integrated the historical development of conceptual models with the traditional content found in a typical grade ten chemistry curriculum. Participants in the research were 74 senior 2 (grade 10) science students from four different classes in three different schools in the province of Manitoba. Prior to, and after instruction, students wrote Lederman's VNOS nature of science test. The tests were reviewed by the researcher and a nature of science profile was compiled for each student. From this profile and the student responses, 24 students (8 from each group) were selected to be interviewed.

The research indicates that the HDCM unit was a successful means to improve students' understanding of models, theories, evidence, and the tentativeness of science. The manner in which students employed their examples in the post-test suggests that the historical content of the unit accounts for this change. On the relationship between laws and theories the research indicates that the view that theories advance to laws is an extremely tenacious misconception although students did seem to improve their understanding of laws and theories independently. The HDCM unit did not yield significant results in advancing students understandings of the creative and imaginative aspects of the nature of science. However, there were individual cases where progress was made which might indicate that more opportunity and a longer development time could enhance student understanding in this area.

Students also indicated positive attitudes towards the inclusion of the history of science in their curriculum. The HDCM unit presented a more humanistic view of science to the students which was reflected in their interest, motivation, and responses to the curriculum. We should view this results as positive for future curriculum development in this area. Finally, the HDCM unit was shown to significantly influence one practising teacher's understanding of the nature of science.

Chapter I

Context of the Problem

Introduction

A recurring theme in science education for well over 100 years has been a concern with the understanding of the nature of science (NOS) [1]. In what is widely regarded as the first modern textbook of science education[2], William Whewell (1840) argued for standards by which science could be judged excellent. By the end of the 19th century, Pearson's *Grammar of Science* (1892) focussed considerable attention on the processes of science and asserted the scientific method as the "sole gateway to the whole region of knowledge" (Jastrow, 1890). As early as 1907, the Central Association of Science and Mathematics Teachers presented an argument for an increased emphasis on the methods of science and scientific processes in science education (reported in Lederman, 1992).

Throughout the early part of the 20th century, John Dewey (1910) advocated that greater attention be placed on inquiry and creativity, and he recommended scientific thinking as the only method compatible with a democratic society. During the major curriculum reforms of the 1960's, Kimball (1968) acknowledged that NOS was a common objective in many curriculum documents and at this time NOS was fostered

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1 In this thesis the term nature of science is used frequently. For simplicity and grammatical purposes the acronym NOS is used to read as "the nature of science".

2 Whewell, William, A History of the Inductive Sciences

through inquiry (Schwab, 1964). Today, at the beginning of the 21st century, NOS outcomes continue to maintain their significance and in the most recent curriculum reforms, NOS is outlined as an essential component of scientific literacy (American Association for Advancement of Science (AAAS), 1993; Council of Ministers of Education Canada (CMEC), 1997).

The expression "nature of science" refers to the epistemology of science and has been characterized by Lederman (1992) as the "values and beliefs inherent to the development of scientific knowledge". Typically, philosophers of science debate such fundamental aspects of NOS as the demarcation of science and pseudoscience, scientific method, and the rationality of theory choice.

Given the complexity of the scientific enterprise, many disagreements exist concerning the specifics of NOS. The structure of NOS has differed among individuals, varied throughout history, and led to many confrontations and philosophical quarrels. The critical arguments of Popper's conjectures and refutations, Kuhn's scientific revolutions, and Lakatos' research programs highlight the diverse opinions outlining this disagreement. However, differing viewpoints among philosophers does not mean that some kind of consensus cannot be reached by science educators on a set of principles and ideas with respect to the nature of science, which are accessible to the high school science student. A reasonable objective for our students would be, to some degree, to become part of the debate by developing a personal view, articulating that view while understanding the strengths and weaknesses of other views. Certainly, at the very least, to be part of this disagreement one must possess a foundation from which to build a personal view.

It should be noted that this thesis mostly addresses students in a high school environment, typically ages fifteen and sixteen years old. Consideration of the characteristics of the learner at this age and grade level are important in the development of any curriculum content. These are learners who may just be beginning to think more abstractly. The fundamental ideas of NOS, as opposed to the sophisticated ideas and argumentation of the philosophers of science, are the ideas which are most relevant to such a young person's science education. The history and development of these ideas are more clearly defined later in this thesis[3] and they align mostly with Lederman's views. Lederman (1998) outlined a set of five general characteristics of NOS which he believes are accessible to K-12 students. These characteristics include that science is tentative, empirically-based, subjective, that science involves human imagination and creativity, and is socially and culturally embedded. Further, he argues for the distinction between observations and inferences, the lack of a single, specifiable scientific method, and a consideration of the relationships which exist between scientific theories and laws. These characteristics, along with the view that NOS itself is dynamic, are the views of NOS associated with this study deemed most relevant to the education of young science students. Later in this thesis, I will also examine the question of consensus and agreement with respect to these aspects of NOS.

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[3] see Chapter II, History of NOS

Research in NOS - A Brief Overview

The understanding of NOS has been a curriculum objective for many years and advanced by many different individuals (Dewey, 1910, Pearson, 1892, Lederman, 1992, for example). Although many aspects of understanding NOS in science education had been proposed as early as the nineteenth century, a collective concern, and corresponding research, began to coalesce with the curriculum developments in the post-Sputnik era of the 1960's. Early studies of students' conceptions of the nature of science led to the formation of several testing instruments including Klopfer and Cooley's (1961) Test of Understanding Science (TOUS) and Rubba's (1977) Nature of Scientific Knowledge Scale (NSKS)[4]. Using these instruments, many researchers concluded that students lacked an understanding of the nature of science (Aikenhead, 1973, Mackay, 1971, Rubba & Anderson, 1978). Munby (1983) criticized these multiple-choice and Likert-type instruments, but later, studies improved on the methodology by incorporating open-ended responses and interview techniques (Lederman & O'Malley, 1990).

In a large Canadian study, using an open-ended instrument, Aikenhead (1987) found that students' answers reflected some ideals of authentic science, such as the nature of classification schemes, tentativeness of models and theories, and the social dimensions of knowledge. However, students emerged less informed on the nature of scientific models, outside influences, motivations for generating knowledge, and on scientific method. Aikenhead also reported that students were not confident with

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[4] These instruments are also discussed in more detail in Chapter III.

discussing these issues, suggesting that their instruction in the understanding of NOS is not well-defined and is assumed implicit with knowledge instruction.

Lederman and O'Malley (1990) also suggested that, on the whole, students did not adhere to either an absolutist or tentative view of science. However, students' responses became more clear when they were given a chance to explain themselves in interviews. In these interviews, students often failed to justify their beliefs, leading Lederman and O'Malley to conclude that "The inability of most students to identify the sources of their beliefs appears to indicate that an understanding of the nature of science is taught and learned implicitly" (p. 235).

The sorry state of the achievement of the understanding of NOS as a goal of science education was also found to be present across disciplines like biology and physics, and, in many countries. Aikenhead (1987) had arrived at a similar conclusion in Canada and Selley (1989) described the traditional British position, "which might be described as a blend of empiricism, inductivism, and naive realism". The poor performance of students' understanding NOS issues began to raise questions about their teachers' understanding of NOS, and subsequently, research began to investigate teachers' understanding of NOS.

Early investigations of teachers' knowledge of the nature of science were critical of the teachers. Miller (1963) reported that a range 11% - 68% of students scored higher on the TOUS than 25% of the teachers (reported in Lederman, 1992). As a result, he concluded that many teachers do not understand science as well as their students.

Schmidt (1967) reported similar findings and concluded a disconcerting proportion of students in Grades 9 and 11/12 were found to score higher than 25% of the teacher sample. Later, other studies seemed to soften this perspective but problems still persisted. Lederman and Druger (1985) detailed that teachers possessed conceptions more adequate than the mean of students in their class (still suggesting inadequacies) but that teacher's conceptions did not match their behaviour in the classroom anyway. This is not to say that some teachers do not have adequate understandings of the nature of science, but the case studies of Hodson (1993) and Lederman (1995) further implied that even when teachers have adequate conceptions of the nature of science, these assumptions do not necessarily influence their instruction in the classroom. In these studies, management and organizational duties were seen as significant constraints on a teachers' ability to plan to teach NOS.

In summary, current research strongly indicates that students possess inadequate knowledge of the nature of science. Moreover, the inability of students to identify sources or influences of their beliefs highlights a paradoxical situation. Regrettably, while clearly stated as a valued goal, the understanding of NOS is often assumed to be absorbed within the content delivery of the discipline. At the same time, research in education clearly demonstrates that the achievement of these goals are suspect, regardless of the methodology which is used in the research. Lederman (1992) reports on a broad range of studies over a period of 30 years and asserts that

> "The overwhelming conclusion that students did not possess adequate conceptions of the nature of science or scientific reasoning is particularly significant when one realizes that a wide variety of assessment instruments were used throughout the aforementioned research" (p 335).

NOS goals in science education have been endorsed by many communities for many years leading Lederman (1998) to also suggest that this longevity "has been surpassed only by the longevity of students' inability to articulate the meaning of the phrase 'nature of science". Research also confirms that teachers lack good knowledge of NOS, and that when they do possess adequate knowledge of the nature of science, this understanding does not significantly influence their behaviour in the classroom.

Classroom Practice and the Curriculum

An understanding of NOS has been a long time goal in science education and research clearly indicates that we struggle to achieve this goal. Yet, many curriculum reforms continue to emphasize this goal in the foundations of their curriculum (CMEC, 1997; AAAS, 1993). What happens between the development of these goals in curriculum standards and the implementation of these goals at the classroom level?

In Canada, teachers are guided by a standard curriculum, commonly referred to as the "designed" or "intended" curriculum. In classroom practice, the teacher controls the implementation of this curriculum and the results are commonly referred to as the "implemented" or "delivered" curriculum. This "filter" can, and does, change the designed curriculum often exposing weaknesses in the intended curriculum as it is implemented in the classroom. Despite this filter, any successfully designed curriculum must first be an enabler for our goals to be achieved through instruction. In other words, the curriculum must permit what we want to happen to happen. For example, a curriculum that promotes inquiry will influence instruction to become more inquiry oriented. A curriculum, like some of the present reforms, which emphasizes the design process, will influence instruction to address design and engineering activities, and lead to related assessment strategies.

The designed curriculum also influences the tools we use. For example, at one time it would have been unusual to find a Geiger counter in a science classroom. In the 1960s, the widespread implementation of the Introductory Physical Science (IPS) course, which included a Geiger counter activity, enabled many science teachers to purchase such equipment to investigate the atomic model of matter. Today, a curriculum which mandates the use of the graphing calculator is without doubt leading to the extensive use of graphing calculators in most classrooms. I am not suggesting that we naively assume that because the designed curriculum enables something to be implemented that it will be implemented. However, the designed curriculum must at least enable our goals. Conversely, there is no doubt that the demise of the IPS curriculum will make it increasingly difficult to find a Geiger counter in a science classroom in the future.

Although we may not always be successful, and teachers may not always read them, the single most influential document in the classroom is the curriculum guide.

While the curriculum doesn't guarantee what will happen in the classroom it does provide the initial impetus to make it happen. However, while many science educators agree that understanding NOS is a valuable goal in science education, the implementation of NOS in the delivered curriculum seems to fall apart. For example, in Canadian science education, a standard curriculum is developed by provincial authorities and teachers implement this curriculum in the classroom. If NOS outcomes are part of this curriculum (and they are) and research clearly indicates that these outcomes are not achieved (which it does), then what happens between our stated goals, the delivered curriculum, and the classroom experience?

Clearly, the designed curriculum is either not adequately enabling the stated intentions for NOS instruction, and/or, teachers in the classroom, for some other reason(s), are rejecting NOS instruction in the implemented curriculum. Gauld (1982) suggests the primary reason for the lack of attention to NOS instruction is the lack of methods for teaching and evaluation, rather than dissatisfaction with the aims. In terms of the curriculum documents, teaching methods for understanding NOS are not addressed but the feeling that evaluation is not possible is reflected in the Pan-Canadian Frameworks for Science Education (CMEC, 1997). The Attitudes foundation of the Pan-Canadian Frameworks, where many NOS outcomes can be found, contends that, "Because of the nature of attitudes no specific learning outcomes are stated" (p. 56).

Gallagher (1991) suggests that the implementation problem of NOS may be because teachers view science as an established body of knowledge since their own science education, and almost all science textbooks, have focused on science as a body of knowledge. Many researchers (Mathews, 1994; Winchester, 1989; Duschl, 1989) have suggested that history and philosophy of science can be a useful means to counter this cycle of teaching the "final form" of science found in the textbook. While a body of research is beginning to form around the use of history and philosophy of science and the attitudes and habits of pre-service teachers (Ab-al-Khalick 1998; Clough, Olson, Robinson, Beisel, & Smasal, 2001), most pre-service teachers are not required, nor choose, to take a course in history and philosophy of science. Gallagher also observes that few educators have any formal education in the history, philosophy, or sociology of science, and he rightfully notes that little opportunity exists to introduce new courses because of the rigid structure of pre-service science education programs. While some programs do exist, it cannot be expected that teachers will, anytime in the near future, have any significant training in the history and philosophy of science and science teaching.

Wade, Lederman, and Bell (1999) argue that the question of why teachers' focus little attention to NOS remains unanswered. For future research, they advise that it is time to turn to the question of classroom practice as opposed to the assessment of conceptions of NOS. Further calls for classroom research has also recently been made by Lederman, Abd-El-Khalick, Bell, Schwartz, and Akerson (2001) who advocate that the present state of research "focus on individual classroom interventions aimed at enhancing learners' NOS views, rather than on mass assessments aimed to describe or evaluate students' beliefs".

However, before I address what we might do in the classroom it is necessary to determine if the present curriculum reforms in Canada have started to adequately address NOS issues. That is, an examination of the extent to which the current curriculum reforms enable or constrain the intended goals of understanding NOS outlined prominently in the curriculum documents.

Curriculum Reform and the Nature of Science

Since the understanding of NOS has been a central aim in past curriculum revisions, we might ask, how do the current reforms address these aims? McComas and Olson (1999) report that a number of recent documents (Curriculum Corporation (Australia), California State Department of Education, CMEC, 1997 (Canada); AAAS, (American), 1993) include a section or chapter specifically dedicated to NOS.

Project 2061 has produced two influential curriculum documents, Benchmarks of Scientific Literacy and Science for All Americans. Benchmarks advocates that the common core of learning should be scientific literacy and that reform in science education must deal with all components of the educational system, including curriculum, teacher education, instruction, assessment, materials, technology, and policy. Benchmarks was intended to be a tool for designing curriculum to meet the standards for science literacy as recommended in the companion document Science for All Americans. It is interesting to note that the first chapter in Science for All Americans is devoted entirely to NOS and discusses the requisite knowledge of the way science works by outlining the scientific world view, scientific inquiry, and the scientific enterprise. A related chapter, "Historical Perspectives", further describes significant developments in the history of science.

In Canada, a similar initiative, influenced by Project 2061, has been the agreement between the Council of Ministers of Education, Canada (CMEC, 1997) to implement the Pan-Canadian Common Framework of Science Learning Outcomes. The Pan-Canadian Frameworks is intended to be an outline for the design of K - 12 science curriculum at the local (provincial) level. The Pan-Canadian frameworks begins with a vision of scientific literacy which leads to a set of four foundational statements intended to guide curriculum outcomes. The vision for scientific literacy is outlined in figure 1 and the four foundations are:

1. Science, technology, society, and the environment (STSE)
2. Skills
3. Knowledge
4. Attitudes

Figure 1:Vision of Scientific Literacy

Scientific literacy is an evolving combination of the science-related attitudes, skills, and knowledge students need to develop inquiry, problem-solving, and decision-making abilities, to become lifelong learners, and to maintain a sense of wonder about the world around them.

An overview of each foundation statement guides the development of a set of general learning outcomes (GLO's) for each grade grouping (K - 3, 4 - 6, 7 - 9, 10 -

12). In turn the GLOs lead to a set of specific learning outcomes (SLO's) for each individual grade. At the grade level, the outcomes are organized according to the Knowledge foundation, and the related outcomes for STSE and Skills are listed. Of interest to this thesis is the STSE foundation (figure 2), which incorporates the understanding of NOS outcomes.

> **Science, technology, society, and the environment (STSE)**
>
> Students will develop an understanding of the nature of science and technology, of the relationships between science and technology, and of the social and environmental contexts of science and technology.

Figure 2: STSE foundation statement

Of particular interest is the GLOs, related to NOS, that are formed for the 10 - 12 grade grouping (#114 and #115, p 76). These GLO's guided the development of the specific learning outcomes (SLO's) for grades 10 - 12 and are shown in figure 3 and figure 4.

Figure 3: General Learning Outcomes #114 for the STSE foundation relating to NOS

NATURE OF SCIENCE AND TECHNOLOGY

General learning outcome 114

Describe and explain disciplinary and interdisciplinary processes used to enable us to understand natural phenomena and develop technological solutions

Specific learning outcomes

114-1 explain how a paradigm shift can change scientific world views

114-2 explain the roles of evidence, theories, and paradigms in the development of scientific knowledge

114-3 evaluate the role of continued testing in the development and improvement of technologies

114-4 identify various constraints that result in tradeoffs during the development and improvement of technologies

114-5 describe the importance of peer review in the development of scientific knowledge

114-6 relate personal activities and various scientific and technological endeavours to specific science disciplines and interdisciplinary studies

114-7 compare processes used in science with those used in technology

114-8 describe the usefulness of scientific nomenclature systems

114-9 explain the importance of communicating the results of a scientific or technological endeavour, using appropriate language and conventions

Figure 4: General Learning Outcomes #115 for the STSE foundation relating to NOS

NATURE OF SCIENCE AND TECHNOLOGY

General learning outcome 115

Distinguish between science and technology in terms of their respective goals, products, and values, and describe the development of scientific theories and technologies over time

Specific learning outcomes

115-1 distinguish between scientific questions and technological problems

115-2 illustrate how science attempts to explain natural phenomena

115-3 explain how a major scientific milestone revolutionized thinking in the scientific communities

115-4 describe the historical development of a technology

115-5 analyse why and how a particular technology was developed and improved over time

115-6 explain how scientific knowledge evolves as new evidence comes to light

115-7 explain how scientific knowledge evolves as new evidence comes to light and as laws and theories are tested and subsequently restricted, revised, or

Even at first glance, it is clear that technology outcomes have become conflated with NOS outcomes in this framework. However, it is not my purpose at this time to critically evaluate the foundations or the individual general and specific learning outcomes of the Pan-Canadian framework (CMEC, 1997). Rather, the intention is to trace the path of the relevant aspects of NOS from the designed curriculum to the implemented curriculum to determine if the latest reform treatment of NOS outcomes, in their stated form, will enhance the achievement of the stated NOS aims.

From the overview of the STSE foundation, it would appear that NOS goals are organized under the STSE statement. Indeed, the description of the foundation outlines the nature of science as “a human and social activity,” and includes reference to creativity, scientific method, and the development of scientific knowledge (Framework, p 9). However, it is not difficult to find other GLOs in other foundations that also depict aspects of NOS, especially in the Attitudes foundation. For example, GLO # 442 reads “confidently evaluate evidence and consider alternative perspectives, ideas, and explanations” (p 198). The difficulty curriculum developers have with attitudes and related NOS outcomes are also clearly identified in the Attitudes foundation where <u>no</u> specific learning outcomes are provided because of “the nature of the Attitudes foundation” (p. 56).

The obvious result of this development of NOS outcomes in the curriculum, besides being a rather confusing format, is that it is impossible to see the “big” picture as NOS outcomes are completely fragmented across the foundations, grades, and content disciplines. In fact, the only way to determine where the NOS outcomes appear is to check each individual grade and knowledge foundation. For example, in the grade 11-12 Physics unit on Fields, the NOS outcomes are 114-2, 114-4, 114-5, 115-3, and, to achieve NOS outcome 114-2, it is suggested that teachers “explain the role of evidence and theories in the concept of fields” (p 238). It might be argued that the only way to attain this objective would be through a historical development. Regrettably, there is no guidance, in terms of instruction, to achieve these NOS outcomes (historically or otherwise) and no connections are made to the knowledge outcomes which are stated in a mostly traditional textbook manner.

Although the level of specificity is quite extensive in the document, the Pan-Canadian Framework is not a curriculum document itself, rather it is intended to guide curriculum developers at the local level. Therefore, it is necessary to further trace the development of NOS outcomes through the provincial curriculum documents.

In the province of Manitoba (MB), the science outcomes are based on those found in the Pan-Canadian framework The MB documents assume the exact view of scientific literacy espoused in the Pan-Canadian frameworks, i.e., "Scientific literacy is an evolving combination of the science-related attitudes, skills, and knowledge" (p1.2). However, while there are four foundation statements in the Pan-Canadian document (see figure 1), in the MB document there are five foundational areas (figure 5). Note that NOS goals now have their own foundation (A). Additionally, each of these foundations consists of a set of six or seven general learning outcomes (GLOs). For example, the goals related to foundation statement A, the Nature of Science and Technology are given in figure 6. From this format, we may think that NOS goals (foundation A) have been isolated, compared to the fragmented view of the Pan-Canadian.

However, we can point to other statements, which also relate to NOS, appearing in foundations B and C (figure 6). Again, at this time, the intention is not to evaluate whether or not these statements are fair descriptions of NOS. Certainly, they fit the

Figure 5: Foundation Statements for Nature of Science and Technology

A1: recognize both the power and limitations of science as a way of answering questions about the world and explaining natural phenomena
A2. recognize that scientific knowledge is based on evidence, models, and explanations, and evolves as new evidence appears and new conceptualizations develop.
A3. distinguish critically between science and technology in terms of their respective contexts goals, methods, products, and values.
A4. identify and appreciate contributions made by women and men from many societies and cultural backgrounds towards increasing our understanding of the world and in bringing about technological innovations.
A5. recognize that science and technology interact with and advance one another.

Figure 6: NOS statements in other foundations

B1. describe scientific and technological developments, past and present, and appreciate their impact on individuals, societies, and the environment, both locally and globally.
B2. recognize that scientific and technological endeavours have been and continue to be influenced by human needs and the societal context of the time.
C4. demonstrate appropriate critical thinking sand decision-making skills when choosing a course of action based on scientific and technological information.
C5. demonstrate curiosity, skepticism, creativity, openmindedness, ...
C8. evaluate, from a scientific perspective, information and ideas encountered during investigations and in daily life.

patterns outlined by the McComas and Olson (1999) review, and I agree that it is easy to argue that NOS goals are integrated and crossover into other foundations. However, there still remains a general confusion surrounding these NOS goals. They are grouped with other nebulous aims like creating attitudes of curiosity and wonder, or they remain isolated from each other failing to provide a "big picture" of what we mean and hope to convey through an understanding of NOS. So, while the document reflects an important role for NOS, the exact character of that role is very difficult to nail down. At this point, I would like to remind the reader that we have yet to track NOS goals to the implementation stage, that is, how teachers actually plan for and teach NOS outcomes at the individual grade levels.

Table 1: MB curriculum clusters

Foundations	Grade Clusters
A. Nature of Science and Technology B. Science, Technology, Society, and Environment (STSE) C. Scientific and Technological Skills and Attitudes E. Unifying Concepts.	Cluster 0: Skills and Attitudes
D. Essential Science Knowledge	Cluster 1: Biology Cluster 2: Chemistry Cluster 3: Physics Cluster 4: Earth Science

In this curriculum format, the general learning outcomes from the five foundations are organized into five clusters at each grade level[5] which contain the specific learning outcomes intended to guide the teacher's instruction. The foundations and clusters do not form a one to one correspondence. Clusters 1 - 4 relate to the

5 The example cited here is the format found in the K - S2 science curriculum. At the time of writing the S3 and S4 science courses were not developed but it is anticipated that they will follow the same format.

outcomes derived from foundation statement D, that is, the knowledge outcomes of life, physical, earth, and space sciences. Cluster 0 outcomes represent the remaining foundations' outcomes that are intended to be integrated into clusters 1 -4 (Table 1).

It is within cluster 0 that we find NOS goals. For example, these NOS outcomes, along with other skills and attitudes are not linked to the specific learning outcomes in the knowledge clusters 1 - 4, it is left to the teacher to choose the context for these outcomes. That is, the same teacher who not only lacks subject area expertise but who has also been shown to lack, or articulate, an understanding of NOS. Ironically, the cluster 0 outcomes may be linked to specific learning outcomes in other subject areas like English Language Arts (ELA) and Mathematics to promote curricular integration. For example, in grade 4, we find NOS outcome 4-0-9a, "Respect alternative views of the world" . This is linked by a code to the ELA outcome 5.1.1 and GLO outcome C5 and C7. Thus, the science curriculum suggests to the teacher how they might integrate the cluster 0 outcomes with English language arts. However, it is left to the teacher to find the context in one, or maybe more, science knowledge outcomes from clusters 1 - 4. Teacher preparation, especially for the early years, in English Language Arts far exceeds their preparation in science. In fact, it is possible that the last general science course an early years science teacher may take would be grade ten science, and in this curriculum, we are asking these teachers to develop the context for the understanding of NOS that curriculum developers struggle to explain. This lack of context creates a significant difficulty for teachers and the isolation of NOS outcomes outside of the knowledge clusters is likely to assign a lower value to these outcomes as teachers struggle to get the content across to their students. In this scenario, NOS becomes "conflated" with skills and either totally ignored or assumed to be taught implicitly. Therefore, it seems likely, that the status quo with respect to teaching NOS will continue, that is, teachers will assume these outcomes are implicitly achieved within the content outcomes. Part of my argument in this thesis is that the NOS outcomes should be integrated with knowledge outcomes using history as a context to achieve both content and NOS aims explicitly.

The prominence of NOS in these curriculum reform documents is characteristic of the status which is given to NOS, the objectives are often stated in the front end of the document but specific outcomes remain sketchy and the implementation of these outcomes is even more questionable.

At the time of writing this thesis the province of Manitoba had started to align its' science curriculum with the Pan-Canadian frameworks. In the meantime, two other provinces, New Brunswick and Ontario have also produced documents based on the Pan-Canadian framework. While I have expressed concerns with NOS outcomes in the Pan-Canadian and Manitoba documents we should note that both documents assign a certain degree of value to these outcomes by expressing aspects of NOS

Figure 7: Ontario Science Goals

1. to understand the basic concepts of science.
2. to develop the skills, strategies, and habits of mind required for scientific inquiry.
3. to relate science to technology, society, and the environment.

throughout their foundation statements. However, Ontario, which is Canada' largest and most influential[6] province, has completely eliminated the foundation statements in favour of three brief goals (figure 7). Further, the learning outcomes in the Ontario science curriculum follow the Pan-Canadian framework very closely in terms of the knowledge outcomes. Technology and skills are very prominent in the outcomes but one is hard pressed to find an outcome which relates to the nature of science. In a word search of the documents from grades 9 - 12, the words "nature of science" never appears, not even once.

Statement of the Problem

The nature of science has been treated as a critical component of the current curriculum reforms. The supporting materials and the "front end" of the documents clearly describe the importance of NOS goals[7]. However, as the curriculum gets closer to implementation NOS goals become fragmented and the context for these goals is left to the teacher who is most likely to emphasize the traditional coverage of content outcomes. Thus, the currently designed curriculum assumes that NOS aims will be achieved implicitly within the content instruction. Unfortunately, research has told us that teachers lack good knowledge of the nature of science, and when they do possess adequate knowledge of the nature of science, this understanding does not significantly

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6 This influence extends to education. The recently marketed science textbooks by Nelson and SciencePower are geared directly to the Ontario market.

7 With the notable exception of the Ontario curriculum

influence their behaviour in the classroom. Consequently, I conclude that recent curriculum reforms will not enhance instruction or improve students' understanding of NOS any more than past reforms.

Lederman also argues that curriculum reforms, present and past, have mishandled NOS goals. He suggests that a "critical flaw" exists in the reform's approach to instruction, and he outlines two general approaches which are advocated by the reform documents and the science education literature. These approaches include "doing science" which emphasizes hands-on, inquiry-based activities, and the historical approach that suggests "incorporating the history of science in science teaching can serve to enhance students' views of the NOS" (p 7). "implicit

Consequently, Lederman offers an explicit, reflective approach as an alternative to the traditional treatment of NOS, and recommends that "The NOS and scientific inquiry be thought of as a "cognitive" rather than as an "affective" instructional outcomes". Moreover, he suggests that "if K - 12 students are expected to develop more adequate conceptions of the NOS and scientific inquiry, then, as any cognitive objective, this outcome should be planned for, explicitly taught, and assessed".

Since an historical approach has been advocated by many educators, this thesis advances a curriculum which explicitly enables NOS outcomes and uses an historical approach to achieve these outcomes. This development is completely integrated within the content discipline while explicitly addressing NOS outcomes. In other words, the curriculum first becomes an "enabler", even for the most inexperienced teacher, by addressing NOS outcomes in a more explicit manner.

The purpose of the research will be to assess students' understanding of the nature of science and how this understanding is influenced by instruction which integrates the historical development of the model of the atom within the curriculum outcomes for the Chemistry unit of the Manitoba Senior 2 Transition science course. The research also investigates student attitudes towards the inclusion of history of science in their science course and the role that students believe history of science may play in understanding theories and models in science. The research was guided by the following questions:

1. How does the historical development of conceptual models (in particular, the model of the atom) influence students' conceptions of the nature of science?

2. What specific aspects of the NOS are influenced by the integration of history of science in science instruction?

3. What are the students' attitudes towards the inclusion of the history of science in their learning of scientific models and theories?

Significance of the Study

A considerable amount of research in NOS appears in the literature. However, the vast majority of this literature pertains to the students' and their teachers' understanding of NOS and not to the development of these understandings. To an extent, some recent research has examined the development of the understanding of NOS in pre-service teachers, but only a handful of studies address intervention with younger students. Additionally, in these studies, the intervention involves a mostly implicit treatment for NOS outcomes and the intervention is only for a short period of time. This study extends the literature by proposing a much longer intervention period which addresses NOS outcomes explicitly using a historical perspective. Finally, in this study, student attitudes toward the inclusion of the history of science are investigated and reported.

Review of the Literature

Chapter II

The History of the Nature of Science

Introduction

> *"There is no institution in the modern world more prestigious than science. Nor is there an institution which, as a whole, is less controversial."*
> Anthony O'Hear (1989, p. 1)

There are few people in the world who do not recognize the significant role science has played in the progress of humankind in the last century, a century sometimes even called "The Century of Science[8]." However, there are many who would object to certain qualities of science. Compelling repercussions of science, such as the "Star Wars" defense systems, nuclear technology, or the confrontation between theories of science and one's personal beliefs, accentuate O'Hear's last claim that nothing else is less controversial. As science cuts across religious, cultural, and political boundaries, our worldviews of science and the nature of science collide. What do we really understand about the nature of science today, and is this understanding relevant to our lives? Imre Lakatos (1973) claimed that the nature of science was "of vital social and

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8 Davis, Watson, *The Century of Science*, 1963.

political relevance" and that the nature of science was serious business with sometimes overwhelming consequences to society and our daily lives[9]. Thus, it seems as critical that we attempt to examine carefully the development of these views with the intention of determining what might be accessible to the high school student, desperately in need of some intellectual relief from the encyclopedic version of science they are presented today.

Recently, I had the pleasure of participating in a friendly but heated discussion on the nature of science with a group of science educators[10]. A concern expressed to me was that we cannot teach the nature of science because of its' controversial nature. Exemplifying this concern, two discussants soon entered into a vociferous debate concerning the cognitive status of scientific concepts and they dominated the group discussion as one consistently took an opposing view to the other. I was asked, in the face of this disagreement, how could we really expect our students to learn anything about NOS? Moreover, what exactly did I want my students to achieve studying NOS? My reply was simple. As an educator we want our students to be prepared to participate in the debate (with perhaps a little more decorum!). To do this, I argued that our students must first understand that controversy is a fundamental characteristic of NOS, then they need to understand the basic beliefs in NOS, the counter arguments of opposing beliefs, and finally, they must be able to articulate their position in a meaningful and convincing

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9 Lakatos refers to the persecutions of the Copernicans by the Catholic Church and the Communist Party of the Mendelians.

10 at the International History, Philosophy, and Science Teaching Conference, Denver 2001.

manner. So, the concern that we cannot teach NOS because we do not agree on the nature of science is not really a concern of the educator. For many years we never agreed on the nature of light (is it a wave or is it a particle?) but that confrontation, and others like it, are not left buried in the minds of a sparse legion. The concern of understanding NOS is not whether or not we should teach it; rather we must ask ourselves, what should we teach? (especially in terms of contentious issues), when should we teach it, and how should we teach it? In the face of the disagreements philosophers of science and scientists themselves have which surround NOS, the answers to these questions are not always obvious.

Lederman (1992) states that the phrase "nature of science" typically refers to the epistemology of science, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge". Although, he does concede that disagreements exist among philosophers of science, historians of science, scientists, and science educators on the various aspects of NOS, he asserts that such a lack of consensus is not alarming. Additionally, Abd-El-Khalick, Bell, and Lederman (1998) contend that "many of the disagreements about the definition or meaning of NOS that continue to exist among philosophers, historians, and science educators are irrelevant to K-12 instruction" (p 418).

In terms of school science, Lederman (1998) outlines the relevant principles of NOS as: scientific knowledge is tentative, empirically-based, subjective, involves human creativity and imagination, and is socially and culturally embedded. He also maintains that NOS is concerned with the distinction between observations and inferences, and relationships between scientific theories and laws. Further, he argues that students need to be able to differentiate between observation and inference. Observations come from our sense data that describes the world around us while inferences are the meanings that we associate with these data. The common view that scientific theories and laws have a hierarchical[11] nature mandates that students must learn the distinction between scientific laws and theories. In the position expressed by Lederman, laws are statements or descriptions of the relationships among observable phenomena, while theories are inferred explanations for observable phenomena. For example, the kinetic molecular theory provides an explanation for our pressure laws. Good scientific theories also often explain observations in more than one domain, guide our investigations, and generate new research problems.

Lederman recognizes that scientific knowledge is, at least partially, based on observations of the natural world but that it also necessarily involves human imagination and creativity by inventing models and explanations. He also accepts that scientific knowledge is theory-laden and that a scientists' theoretical commitments, beliefs, experiences, and expectations influence how they make sense of and interpret their observations.

The view that science is a human enterprise practiced in the context of a larger culture is outlined by Lederman when he claims that science is affected by the "various

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11 McComas (1996) cites this as the #1 myth of science. That is, the belief that theories become laws when sufficient "proof" is gathered. In this view scientific laws have a higher status than scientific theories.

elements and intellectual spheres of the culture in which it is embedded". Finally, he states that scientific knowledge is never absolute or certain, but that it is always tentative and subject to change. Change occours as new evidence emerges or new ideas fosters new interpretations of old evidence.

While I believe that the characteristics of NOS as outlined by Lederman are useful for science education, he fails to adequately address two issues surrounding these claims. First, he fails to illustrate how these ideas emerged from science in the first place and secondly, he advocates a particular view of NOS[12] and neglects to outline how the educator needs to address some of the more controversial issues of NOS.

This leads me to address the first of my concerns with Lederman's characterization of NOS, that is, his failure to elucidate on the origins and developments of these ideas. To do this not only helps us understand the nature of the controversies surrounding NOS but also supplies the educator with a solid background for developing his or her own views on the nature of science. One means of expanding on the origins and development of NOS views is through a descriptive approach, such as advocated by Gerald Holton.

Gerald Holton (1984), the eminent Harvard scholar and physics educator, notes the indifference that practicing scientists have toward the musings of modern philosophers of science.

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12 In the instrumentalist view, our models, laws, theories, and the entities they postulate, are nothing more than useful devices to explain and predict phenomena in the natural world. Lederman's personal commitment is admittedly instrumental as he declares that "scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality".

> "the perception by the large majority of scientists, right or wrong, that the messages of more recent philosophers, who themselves were not active scientists, are essentially impotent in use, and therefore may be safely neglected" (p 123)

Today's philosophers of science advance a highly prescriptive philosophy of science specifying the standards by which scientists should practice and how they should evaluate their scientific theories. Holton's answer to this type of legislative directive was to develop a descriptive philosophy of science to reveal the methodology and evaluative procedures which have actually informed science. In his view, a historical review of the sources is essential to identify the thematic principles germane to the development of scientific thought pertaining to the understanding NOS. How could we ever isolate the scientist from his thoughts of science and his practice? Laudan (1969), on the evolution of scientific method adds, "the historian of science must deal with this issue continually because the views of particular scientists on questions of methods clearly cannot be ignored when we explain their scientific theories and procedures" (p. 2). I believe that a descriptive approach is relevant, not just to the scientist and the interested philosopher, but also to the science educator.

Losee (1993) outlines the view adopted in this thesis that the philosophy of science is a second-order criteriology. That is, the first level is that of facts, the second is explanation of facts, and the third is the analysis of the procedures and logic of scientific explanation[13]. According to Losee, the philosopher of science seeks answers to questions

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[13] Losee numbers these 0, 1, 2, hence a second order criteriology

as:

1. Demarcation, what distinguishes scientific questions from other modes of thinking (like religion).

2. What is scientific method? What are the procedures that scientists should follow in investigating nature?

3. What is truth and who gets to decide what is true? What conditions must be satisfied for a scientific explanation to be correct?

4, What is the cognitive status of scientific laws and principles?

There is a difference between doing science, thinking about science, and teaching science. The distinctions are not always clear and the domains will always remain interrelated, however Losee observes that

> "The scientist who is ignorant of the precedents in the evaluation of theories is not likely to do an adequate job of evaluation himself. And the philosopher who is ignorant of scientific practice is not likely to make perceptive pronouncements on scientific method" (p 3)

I would like to add that the educator who is neither versed in the role of the scientists nor in the views of the philosopher, will remain doomed to merely transmitting a meaningless collection of scientific facts. In this sense, understanding and teaching NOS serves to open the minds of our science teachers, and thus reflects a more authentic, meaningful development of science for their students.

It is appropriate to provide an overview of the history of NOS which will establish and emphasize the dynamic nature of NOS itself. In this way, we can identify the recurring themes and controversies that have woven their way through time. For this purpose, it is necessary to highlight the ideas of several philosophers and scientists throughout history who have made significant contributions to understanding the nature of science in terms of scientific explanation, demarcation, methods of science (including induction, deduction, hypothesis), and the controversy between a priori and empirical elements of science. This review will outline a perspective for the science educator in order to establish a historical portrait which might enable the educator to make intelligent choices for what should be taught to achieve a more philosophically valid curriculum in science education today. Consequently, my review necessarily surveys the early ideas of the Greeks, the reflections and contributions of Medieval and Renaissance logicians, the major leaps of the scientific revolution and the emergence of new and controversial theories of 19th and 20th century science.

Early Ideas from Greek Science

Thinking about the nature of science has a long and confrontational history. The natural philosophers of science from the earliest times argued carefully about what constitutes science explanation, how scientific knowledge develops, and what are the questions and methods of science. Early thinkers began to speculate on the natural events that unfolded around them, disengaging them from the practical, and considering them for the love of knowledge as opposed to the efficacy of their craft. Initially, these wise men were called philosophers or lovers of wisdom[14], a term of praise applied to

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14 Whewell, p 19

their sagacity. They not only developed an appreciation of nature but also they emphasized an appreciation of the nature of their explanations, their modes of thought, and the fundamental questions they asked.

The first recorded important contributions to Greek science came from the city of Miletus, near the coast of what is now Turkey, beginning with Thales in about 585 B.C., followed by Anaximander about 555 B.C., then Anaximenes in 535 B.C[15]. These early philosophers were the first to do real science as we know it, rather than cultivating the craft tradition or developing new technologies. By this, we mean that they began to provide explanatory systems for natural phenomena such as lightning, earthquakes, and lunar eclipses. They explained the events around themselves in terms of natural laws instead of arbitrary acts by gods. For example, Anaximander suggested that lightning was caused by clouds being split up by the wind.[16] They also contemplated fundamental questions of science such as the origins of life, the genesis and fate of the universe, and the structure of matter.

However, unlike 20th century science, the ancient Greeks, widely recognized as the forefathers of modern science, never differentiated between science and philosophy as separate modes of inquiry. The first two books in *Aristotle's Physics* clearly explicate a philosophical position on nature and the study of nature. The nature of the celestial and terrestrial realms, and our place at the centre of the universe, greatly influenced and was

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15 for an extended discussion of their contributions to science see Lloyd, G. E., 1970

16 which in fact is not an unreasonable conjecture

taught alongside many of the early scientific principles. Indeed, a guiding principle of the Greeks was the need for psychological satisfaction, and their spiritual hierarchy and cosmology was integrated with, and helped give meaning to, their deliberations.

Aristotle laid the foundations of the first detailed, logically connected and comprehensive picture of the world. His writings, a synthesis of his own ideas and those of previous natural philosophers, inspire, even today, our thinking and understanding of the nature of science. E.H. Beth comments, "it was Aristotle who ... set forth a theory of science, which for centuries to come directed and even dominated scientific thought."[17] Aristotle's views provided a glimpse into not just thinking with scientific theories but thinking about scientific theories and demanding a means to establish what constitutes a good scientific explanation.

Aristotle considered scientific explanation as a transition from knowledge of a fact to knowledge of the reasons for the fact[18]. Aristotle viewed scientific inquiry as a cycle which progressed from observations (by induction) to explanatory principles about those observations, then back to observations (by deduction). This was done by drawing information from our sense experiences and by induction proceeding to generalizations. From these generalizations we then deduce consequences about the phenomena in question.

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17 quoted from Laudan, *Theories of Scientific Method*, p 13

18 Aristotle discusses this in *Posterior Analysis* using the eclipse of the sun and the earth shaking as examples. Once we notice the fact that the sun is eclipsed, or the earth is shaking, we proceed to inquire the reason for the observation.

In his method, there are two types of induction[19], simple enumeration and direct intuition. In simple enumeration what is observed to be true of several individuals is presumed to be true of the group. That is,

If,	a_1 has property P,
And,	a_2 has property P, a_3 has property P.
Therefore,	all a's have property P.

In direct intuition, induction is a matter of insight. It is the ability to grasp what is essential in our sense experiences. This is an ability which is achieved after extensive experience as the observer learns to "see" certain attributes. It is more than simple enumeration (counting) and involves judgement to be made on the importance or relevance of multiple factors. Aristotle is sometimes criticized[20] for his reliance on simple induction as others soon recognized some of its serious limitations. One such problem is that we can never generalize a universal proposition from a limited set of observations since we are unable to ever conclude that a contrary case does not, or will not, ever exist.

In the next phase of Aristotle's scientific inquiry, the generalizations reached by induction are used as a premise for the deduction of statements about the original observations. Upon application of the deductive stage the scientist has advanced from

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19 Aristotle outlines this method in Book I of his *Prior Analytics,* for example see Barnes, J. p41 ff. Also see Losee, p 6 , Ross, W. D., p 552

20 Bacon for one in his Opus Major

knowledge of a fact to an explanation of the fact. Aristotle used the syllogism[21] as a means of deduction. A syllogism has three statements, a premise, a middle term and a conclusion. The form of a syllogism is:

	All M are P,
	All S are M,
therefore,	All S are P.

For example,

	All mammals bear their young alive.
	All whales are mammals.
Therefore,	All whales bear their young alive

In this form of logical deduction, different arguments result when different middle terms are selected and some of these arguments are better than others. Aristotle recognized that a conclusion could be reached from several different premises so he established a set of rules to evaluate the validity of the syllogism[22]. For the conclusion to be valid the premise must be true, better known than the conclusion, and causally related to the conclusion (the opposite of causally related would be accidental correlations).

Also emerging from Greek science was the belief that the structure of a completed science would be a deductive system of statements originating with self-evident truths. Furley (1999) states that Aristotle's *Posterior Analytics* were generally

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21 Aristotle outlines this method in his *Posterior Analytics,* for example see Barnes, J. p114 ff. Also see Losee, p 9 ff

22 Aristotle explains these rules in An. Pr. 25a5-13 and An.Pr. 25a14-26, the specific examples used here are adapted from Tom Bridges.

held to describe the way in which science should be presented and that this system tends to suit the mathematical sciences more closely. The ideal of a deductive science could be a system not unlike Euclid's synthesis of geometry[23]. In his book, the *Elements*, Euclid had formed systems of statements such that the truth of the theorems followed from the assumed truth of the axioms. Three requirements must be met in order to prove theorems:

1. Axioms and theorems must be deductively related.
2. Axioms are self-evident truths.
3. Theorems must agree with observations.

The method of proof in this system is reductio ad absurdum, a form of refutation where logical deduction from the premise results in contradictory or absurd consequences. An extension of reductio ad absurdum is proof by exhaustion which demonstrates that every other hypothesis, except the true one, involves an absurdity. For example, this method is illustrated in Proposition 1 of Archimedes' Measurement of the Circle. In his proof, Archimedes computes the area of a circle from polygonal approximations using a shrewd double reductio ad absurdum argument combined with the ``method of exhaustion''.[24]

A criticism of the ideal system of deduction relates to the meaning of the terms of the deductive system with respect to their behavior in the physical world. The problem is that the terms in an ideal system do not always yield the same attributes in the real world. For example, Archimedes, in describing his law of the lever, would necessarily consider

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23 Losee, p 23

24 T. L. Heath (ed.) The Works of Archimedes, [16, pp. 91--93,] Dover, New York.

the lever to be an infinitely rigid but massless rod. In any real situation though, a lever has mass and will bend[25]. Aristotle's inductive-deductive cycle and the logic of deductive proof provided a means for Aristotle and the early philosophers to think about the nature of scientific explanation instead of merely thinking with scientific principles. But what do we explain with these principles? The nature of science, closely scrutinized by religious ideals, demanded a demarcation for the questions of science.

McKeon (1947) reminds us that "The Aristotelian analysis of sciences depends on the differentiation of mathematics from physics" (p. 44) and Aristotle offers that "the question whether what is one and unchangeable, does not belong to a discussion of nature"[26]. For Aristotle, the subject matter of science was change, and mathematics was concerned with that which is not changing. Aristotle also outlined that in science, each discipline has essential attributes, or a structure which guides the discipline. These principles are not subject to deduction from more basic principles. Aristotle called them "necessary truths" that mirrored nature which could not be other than the way it is. For example, a first principle in the domain of physics would be that an object's natural motion is motion toward the centre of the earth. This kind of teleological cause presupposes that a future state determines how the present materializes. Fire rises in order to reach its' natural place (between the earth and the moon), and terrestrial objects fall to achieve their natural place at the centre of the universe.

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25 Losee, p 26

26 *Aristotle's Physics*, book I, Ch.2 p2. Translation by W. Charlton. See also a discussion of Aristotle's view of change in Furley, p 12.

Another influential early view of the questions of science had been advanced by the Pythagoreans' belief that mathematics reflected the structure of nature. In this orientation, mathematical relationships counted as explanations of natural phenomena. Plato himself, adopted a mathematical view and is reputed to have inscribed over the entrance to his Academy "let no one destitute of geometry enter my doors". Plato's philosophy reinforced a commitment to the Pythagorean system, (the Pythagorean solids became his ideal bodies) as he sought to explain an underlying rational order in terms of these solids. For example, elements, represented by the regular solids, transmuted from one to another through the recombination of their triangular faces[27].

Plato set in motion the events that would herald one of the most controversial aspects in the nature of science. Plato challenged his pupils at the Academy to develop a geometrical system to explain the motion of the heavens to "save the appearances."[28] Eudoxus proposed a geocentric system of homocentric spheres while Aristarchus solved the problem with a daily rotation of the earth in a heliocentric system. Heraclitus arrived at a partially heliocentric system with Mercury and Venus orbiting the sun and the sun and the rest of the planets orbiting the earth[29]. It was obvious that all three models could not be correct, but did they merely account for the observations that we can make about

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27 Losee, p 19

28 see Blake's Theories of Scientific Method. Blake credits this famous phrase to Plato himself. A hypothesis is said to save the appearances when it accounts for the observations we make but is not necessarily true.

29 Kuhn, T. The Copernican Revolution. It is not the intention here to discuss these systems in detail but information concerning the observations and the explanatory systems can be obtained from the first three chapters of Kuhn.

the motion of the planets and stars or, was one of the models actually a reflection of the way the universe really was? The confrontation of the realist view as opposed to an instrumentalist view of explanation epitomizes a fundamental controversy in the nature of science which would re-emerge throughout the ages.

Aristotle imposed a realists' interpretation on the two-sphere system of Eudoxus whereby the planets were carried around by hard crystalline spheres. The spheres of each planet were in contact with each other and the movement of the outer sphere of stars was passed to the inner planets by the rubbing of adjacent spheres. Later, Ptolemy added epicycles and eccentrics to the geocentric model of the solar system in order to achieve a more accurate agreement with the observations of the planets. However, the inclusion of the epicycles whereby the planets moved in their own circles, seemed to contradict Aristotle's realist view of the hard spheres carrying the planets. Consequently, Kuhn (1957) reports that attempts to provide a mechanical explanation of epicycles were largely ignored and the real existence of the crystalline spheres was questioned. Thus, astronomers began to adopt an instrumentalist view of the Ptolemaic system. That is, the system was useful for computation purposes only and did not really describe what the universe was really like. It is not clear from the Almagest if Ptolemy supported this view but he did suggest that if it came to a choice between two empirically adequate theories then the simplest theory should be selected.[30]

The Instrumentalist view versus the Realist view was, and remains, a classic

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[30] see Kattsoff, Isis, xxxviii, 1947, p 85

confrontation in the nature of science, and the controversy was passed on when the Ptolemaic system was compared to Copernicus' new ideas in the fifteenth century. Surprisingly, Copernicus' heliocentric solar system was not in agreement with astronomical observations any better than Ptolemy's system until Kepler refined the model more than 60 years later[31]. Indeed, Copernicus had been forced to resort to the epicycles of Ptolemy to achieve a comparable quantitative account of the motion of the planets[32]. Whewell (1840), referring to epicycles and eccentrics, also noted that "The heliocentric theory, without these appendages, would not approach the Ptolemaic, in the accurate explanation of the facts" (p. 275). Was this mathematical scheme nothing more than a computational device merely "saving the appearances" of the phenomena or did it reflect the underlying reality of nature? Many questions in the nature of science are highlighted by this controversy such as how do we decide between competing theories that equally explain the phenomena? For some, the choice between several theories, all of which saved the appearances, was the theory which reflected the underlying structure of nature. For others, the purpose of the theory was simply to save the appearances.

While the Pythagoreans held the view that the underlying mechanism of nature was mathematical harmony, the proponents of Atomism believed that this underlying nature was discrete. Atomism has its roots in Greek science suggesting that natural phenomena can be explained by underlying mechanisms functioning at a more

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31 See Kuhn, T. Objectivity, Value Judgement, and Theory Choice, p 104

32 See Kuhn, T. The Copernican Revolution, p 169 for a comparison of Ptolemaic and Copernican epicycles.

elementary level in the micro-world. In the fifth century B.C., Leucippus and Democritus proposed a universe which was filled with minute indivisible particles called atoms. However, the acceptance of atomism met resistance in terms of its materialistic outlook and nonmaterial values. Losee adds "By explaining sensation and even thought in terms of the motions of atoms, the atomists challenged man's self-understanding" (p 28). It is not difficult to understand how a controversy could surround the assignment of one's behavior to the movement of atoms.

The contention that the underlying mechanism of nature was discrete, continuous, or that it reflected a mathematical harmony are aspects of NOS which continue to attract our attention today. Unfortunately, the atomic theory, the nature of light, or the Copenhagen interpretation are just a few of the prevailing questions our students are asked to consider without respect to some of the more fundamental queries motivating these deliberations.

Medieval Period

For many years, science thrived throughout the early medieval period and in other cultures such as Egypt and the Arab world. Arab science had flourished during this time with the evolution of a numeric system, increasingly more accurate time-keeping devices and astronomical instruments[33], optics, and medicine[34]. Eventually, classical knowledge, including the early expositions, such as Aristotle's works and the Almagest, were carried to Latin Europe as the scientific climate in Europe improved in the late medieval period with the creation of the first universities.

Beginning in the twelfth century, much of Aristotle's work became available in Latin through the work of the great translators Gerard of Cremona at Toledo (1114 - 1187)[35] and William of Moerbeke (ca. 1215 - 1286)[36]. Scholars were introduced to the philosophy of the Greeks through Aristotle's works and commentaries on these works by learned men such as Averroes (1126 - 1198), Alkindi (ca. 801 - 873), and John Philoponus (ca. 490 - 570). Aristotle's writings on science and scientific method had been translated into Latin by 1270 and these writings, directed the attention of philosophers toward natural science[37]. The translations spurred a lengthy debate and "for several generations the standard presentation of a work on a particular science took the

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33 For more detailed information on Arab astronomy see Goldstein, "Theory and Observation in Medieval Astronomy", ISIS 63, p 39 -47; also Saliba, George, "Theory and Observation in Islamic Astronomy: The Work of Ibn al-Shatir", Journal for the History of Astronomy 18, p 35 - 43.

34 Huff, Toby (1995). *The Rise of Early Modern Science*. Huff suggests that although Islamic science was devoted to study of the Quran, legal knowledge, and theology, many traditions gave rise to several advancements in what was referred to as foreign science. Arithmetic was developed for the purposes of dividing inheritances, geometry and trigonometry to arrive at the correct time and directions to Mecca for prayer. Until its decline in the thirteenth century Huff implies that Arab science was close to giving rise to modern science

35 For a complete listing see McVaugh, Michael, in Grant, E. p 35 -38.

36 For a complete listing see Grant, E in A Sourbook of Medieval Science, p 39 - 41.

37 Crombie, *Grossteste and Experimental Science*, p 35

form of a commentary on the corresponding study by Aristotle"[38]. Crombie[39] calls Aristotle a tragic hero striding through the middle ages from Grosseteste to Galileo "seducing men's minds by the magical promise of his concepts, exciting their passions and dividing their allegiances". Aristotle's views became immediately controversial as scholars and theologians attempted to reconcile their philosophical views with a Christian doctrine. In spite of a Paris ban[40] on Aristotle's books, the richness of their content "led to their inclusion in medieval university curriculum, and by 1255 Aristotle's works formed the core of medieval university education"[41] in Paris, as they had continued to be in Toulouse, Montpellier, Bologne, Oxford, and Cologne.

The Medieval period both built upon and revolutionized our understanding of NOS. A growing interest into the rational inquiry of the nature of things helped lay the foundation for a critical view of Greek science. Medieval philosophers analyzed and critiqued Aristotle's positions with respect to scientific method, the evaluation of competing theories, and the nature of scientific knowledge as necessary truth. Crombie[42] notes that during this period "In their study of these problems the medieval philosophers

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38 Losee, p 31

39 Crombie, A.C. (1959), Medieval and Early Modern Science, p 1

40 Thorndike, Lynn. The Condemnation of Aristotle's Books on Natural Philosophy in 1210 at Paris, translation from Chartularium Universitatis Parisiensis, ed. H. Denifle and E. Chatelain, Paris, 1889 - 1897, in *A Sourcebook in Medieval Science,* ed. Edward Grant, p42, 1974.

41 Grant, E. The Condemnation of 1277, translation from Chartularium Universitatis Parisiensis, ed. H. Denifle and E. Chatelain, Paris, 1889 - 1897, in *A Sourcebook in Medieval Science*. ed. Edward Grant, p 45, 1974

42 see Crombie, A.C. (1959), *Early and Medieval Science*

investigated the logical relationship between facts and theories, or data and explanations, the processes of the acquisition of scientific knowledge, the use of inductive and experimental analysis to break down a complex phenomenon into its component elements, the charter of the verification and falsification of hypotheses, and the nature of causation" (p. 7)

Although not known for revolutionizing the principles of science, medieval philosophers like Robert Grosseteste (c.1168 - 1253) made lasting contributions through their reflection on the nature and methods of science. Grosseteste was a scholar and teacher who became Chancellor of Oxford University during its early period. He was a practicing scientist who explored the fields of optics, calendar reform, heat, tides, and sound[43]. He thought about, wrote about, and unlike many other scientists cum philosophers, practiced a model of scientific experimentation that extended Aristotle's ideas of verification of scientific theories to include the ideas of falsification and the uniformity of nature, and the formation of principles, such as parsimony, for evaluating rival theories. Grosseteste melded his deliberations on the nature of science with his practice of science and he used his analyses of optics and astronomy on comets and stars[44] to support many of his claims.

Grosseteste adapted Aristotle's inductive-deductive approach to science moving from experience to theory and then from theory back to experience. He noted that

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43 For considerable more detail on Grosseteste's scientific accomplishments see Grant, p 384, p 640 and Crombie, especially chapter V.

44 See Crombie, p 87 for some examples. A thermodynamic example of Grosseteste is described on the following pages.

Aristotle's method of induction had been one of mostly enumeration, or of simple counting of instances. Grossteste, perhaps influenced by Galen's work, or possibly guided by the writings of the Arabic doctor Alkindi on medical diagnosis[45], extended this method of induction to one of "Resolution" and "Composition". Commenting on Aristotle's *Posterior Analytics,* he acknowledged, "there is a double way with already existing knowledge and knowledge, namely, from the more simple to the composite, and the reverse, from principles and from the effect"[46] . Grosseteste referred to this inductive-deductive cycle as a method of resolution of facts about phenomena and the composition in which these components are recombined to form the original phenomena. He began by collecting examples of the phenomenon and then he sorted and classified these instances by likeness and difference. A causal connection was suspected when many instances would be found frequently grouped together. Then in the process of resolution, the propositions were rearranged to show that the specific instances could be deduced from a more general proposition demonstrating a cause and effect relationship. On the relationship between cause and effect Grosseteste wrote

> "since there is no effect that has not some cause, it follows that an effect, just as it has one cause, so it may have another, and so there may be several causes of it"[47]

and he recognized a number of weaknesses with the explanation of cause. First, as just

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45 Crombie, Grosseteste, p76

46 quoted from Crombie, Grosseteste, p 52

47 Crombie, Medieval and Early Modern Science, p 15. from book 2, chapter 5 of Grosseteste's commentary on the *Posterior Analytics.*

stated, there could be many causes which might produce the same effect, consequently science could offer its' explanations only as "probably rather than scientifically".[48] Additionally, if there were many possible causes he recognized the need for some means of deciding between causes. He proposed a logical argument that could be followed to determine the true cause by eliminating all but one of the hypotheses. This method, called a *modus tollens* argument, can be used as follows (where T is theory and O is observation):

> If T then O,
> not O,
> then not T

Although this form of logical argument was used in mathematical deduction since the time of Euclid[49], Grosseteste's contribution was to apply the method systematically to extend Aristotle's evaluation of a scientific hypothesis. Grosseteste applied his method of falsification to his hypotheses on Comets, on the rainbow[50], and on heat. For example, to account for the generation of heat from the sun he claimed that

> If the sun generates heat by conduction, then the adjacent celestial matter is heated and undergoes a change of quality;

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48 Crombie, Medieval and Early Modern Science, p 16. from book 1, chapter 11 of Grosseteste's commentary on the *Posterior Analytics.*

49 for example see Euclid's proof that there is no greatest prime number in his *Elements*, Book IX, proposition 20.

50 for examples on the comet and the rainbow see A.C. Crombie, Medieval and Early Modern Science, p 18.

> But the adjacent celestial matter is immutable and does not undergo a change of quality;
>
> Therefore, the sun does not generate heat by conduction[51]

Of course, the hypothesis is valid only if it's premise is true so Grosseteste's conclusion in this case is unconvincing in retrospect. However, the method of falsification was a useful form of argument and was adapted by other scientists. John Buridan[52] applied this form of falsification to his refutation of Aristotle's explanation for projectiles as follows:

> If the air in front of a projectile rushes around to prevent a void, thereby pushing the projectile forward then an arrow with a blunt end should move faster than one with a pointed end;
>
> An arrow with a blunt end does not move faster than an arrow with a pointed end.

Therefore, since the second premise is observed to be false, the explanation for projectile motion is also false and calls into question additional aspects of Aristotle's physics[53].

Grosseteste had based his method of falsification on two presuppositions about nature. First, he believed in the uniformity of nature and secondly, he said

> "that demonstration is better, other circumstances being equal, which necessitates the answering of a smaller number of questions for a perfect

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51 A. C. Crombie, "Grosseteste's Position in the History of Science, in Robert Grosseteste, ed. D. A. Callus (Oxford: Clarendon Press, 1955), 118.

52 see John Buridan, "Questions on the Eight Books of the Physics of Aristotle, Book VIII, Question 12, reprinted in M. Clagett, The Science of Mechanics in the Middle Ages (Madison, Wis.: University of Wisconsin Press, 1959), 533

53 note: Buridan never claimed to have actually performed the experiment.

> demonstration, or requires a smaller number of suppositions and premises from which the demonstration proceeds".[54]

In other words, he is stating a form of a principle of parsimony which holds that nature is economical and operates by the shortest means possible. Grosseteste employed this principle in support of his laws of refraction[55].

Further discussions on the certainty of knowledge and improvements to the method of induction were made by other writers after Grosseteste, notably John Duns Scotus and William of Ockham. In the Duns Scotus' method of agreement one looks for a particular effect that is present in every case under investigation. The procedure is summarized in table 2. In this case, one can conclude that "e" *can be* the effect of cause "A".

Table 2: Method of Agreement

Case	Cause	Effect
1	ABCD	e
2	ACE	e
3	ABEF	e
4	ADF	e

On the other hand, William of Ockam formulated a procedure for drawing conclusions by a method of difference. In this method we compare two cases, one in

Table 3: Method of Difference

Case	Cause	Effect
1	ABC	e
2	AB	-

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54 Grosseteste, from his commentary on *Posterior Analytics*, book 1, chapter 17, in A.C. Crombie, *Medieval and Early Modern Science*, p 17.

55 A. C. Crombie, *Robert Grosseteste*, p 119 - 125. Grosseteste believed that the angle of refraction was one-half the angle of incidence. He choose the ratio 1:2 because he believed that nature follows the simplest course and the ratio 1:1 was taken by the laws of reflection.

which the effect is present and one in which the effect is absent. If the cause is present when the effect is present and absent when the effect is absent then one can conclude that "C" can be the cause of "e" (table 3). William of Ockam also applied a criterion of simplicity to his understanding of nature. For example, he maintained that to say a body moves because of an acquired impetus is to say no more than a body moves and he recommended the elimination of the concept of impetus[56].

Additional philosophers of the late medieval period took up Grosseteste's concern with the nature of science and their contributions formulated early but sophisticated ideas of a theory of experimental science and of scientific method. Roger Bacon, a student of Grosseteste's, advocated that the inductive stage of science could be augmented by a test of further experience. Bacon's works, including his *Opus Majus,* also proposed reforms in education and emphasized the importance of mathematics and experimentation and the study of the natural world using observation and exact measurement.

The views of the late medieval period on the nature of science can serve as a model for many ideas of NOS which might be accessible to secondary students. Although commonly known as a quiet period in the history of science, the medieval philosophers seem unfairly neglected for their contributions to science especially for their reflection on, and extension of, the methodology of Aristotle.

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56 Losee, p 39

The Scientific Revolution

The Pythagorean view that mathematical harmony was the underlying structure of nature continued to create controversy during the Copernican scientific revolution. Nicolaus Copernicus (1473 - 1543) sought to reform Ptolemaic astronomy by eliminating certain aspects of the geocentric system of the universe such as equant points, and by placing the sun at the centre of the planetary motions. The debate concerning saving the appearances resurfaced with the publication of Copernicus' *De Revolutionibus* as Osiander tried to convince Copernicus to acknowledge that his system was just a hypothesis for which only mathematical truth could be claimed. However, Copernicus believed in the underlying mathematical harmony of his system, and that the structure he proposed was really there and was not just a computational device. Osiander wrote, without Copernicus' knowledge, a preface to his book denying the physical truth of the system but Copernicus died before confronting Osiander over the unauthorized preface. However, the debate over "saving the appearances", passed on since the days of Plato, lived on through the ensuing dispute between Cardinal Bellarmine and Galileo Galilei over the nature of the Copernican system. Galileo assumed the role of the realist believing that the Copernican system of the universe modeled physical reality writing that "since that constitution is, and is in one way only, true, real and impossible to be otherwise".[57]

In 1615, Cardinal Bellarmine advocated an instrumentalist interpretation and

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57 Galileo Galilei, Istoria e dimostrazioni intorno alle macchie solari, in Le opere, V, 102. as quoted from Blake et al, Theories of Scientific Method, p 44.

expressed publicly that Galileo must restrict himself to speaking of the theory of Copernicus only as a basis for mathematical computation.

> "To say that on the supposition that the earth moves and the sun stands still all the appearances are saved better than on the assumption of eccentrics and epicycles, is to say very well - there is not danger in that, and it is sufficient for the mathematician: but to wish to affirm that in reality the sun stands still in the center of the world, and only revolves upon itself without traveling from east to west, and that the earth is located in the third heaven and revolves with great velocity about the sun, is a thing in which there is much danger not only irritating all the scholastic philosophers and theologians, but also on injuring the Holy Faith by rendering false the Sacred Scriptures"[58].

Bellarmine rightfully points out that to show that a hypothesis saves the appearances is not the same as demonstrating physical truth. He admits that if "there is a real demonstration that the sun stands in the center of the world" that theologians would have to rethink their interpretations of the scriptures. However, Bellarmine doubted that any real demonstration of a movable earth could be made. Of course, Galileo believed that the Copernican system did represent the physical truth so much so that he offered as support an explanation of tides which was obviously wrong[59]. As is well known, Galileo greatly overplayed his hand in his *Dialogue Concerning the Two Chief Word Systems.*[60]

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58 Roberto Bellarmine a Paolo Antonio Foscarini, Roma, 12 aprile 1615, in Galileo Galilei, Le opere, XII, 171 - 172, as quoted from Blake et al, Theories of Scientific Method, p 44 - 45.

59 see Losee, p 61 for Galileo's theory of tides.

60 Galileo was forced to recant his support of the Copernican model and was placed under house arrest. for a brief outline see Kuhn, T., *The Copernican Revolution*, p 199 ff.

Galileo, like most of the great philosophers, contemplated the underpinnings of his work and believed that the "book of nature" was written in mathematics as he sought to demarcate between the fields of mathematics and physics. According to Galileo, the role of physics was not to investigate the metaphysical world but to explain the physical world especially in terms of the qualities which could be represented mathematically. The scope of his physics was restricted to the primary qualities of shape, size, number, and position rather than the secondary qualities of colours, taste, odour which found their meanings in the mind of the observer[61].

Galileo, like Grosseteste, also ascribed to Aristotle's inductive - deductive methods (resolution and composition) and asserted the idea of abstraction to the ideal case (ex. free fall, the ideal pendulum). Galileo commonly developed new hypotheses from some intellectual intuition, subjected them to thought experiments and abstraction to an ideal, followed by mathematical analysis. Additionally, experimentation was employed to falsify or confirm hypotheses and then further tests of experience were used to extend new ideas to new situations. Galileo often used thought experiments, for example, in the development of the concept of inertia, Galileo describes in his *Two New Sciences,*

> "For in the case of planes which slope downward there is already present a cause of acceleration; while on planes sloping upwards there is retardation; from this it follows motion along a horizontal plane is perpetual; for if the velocity be uniform it cannot be diminished or

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61 Galileo, in Drake p 274

slackened, much less destroyed".[62]

Of course, Galileo could not perform such an experiment but his conclusion was an impressive innovation compared to previous notions of force and motion. Motion was no longer a cause and effect phenomena but a state of the object. Motion persisted indefinitely and force could now be thought of something that caused a change in motion. Subsequently, Galileo could extend this new concept to calculate the path of a projectile as the combination of uniform and accelerated motion. He also extended these ideas to new situations when he predicted, without experimentation, that projectiles launched from equal increments before and after 45°, would have the same range.

Galileo's abstraction to an ideal world were not without inherent drawbacks. Galileo, searching for evidence to support the Copernican system, offered as his principle argument a theory of tides which obviously contradicted known patterns[63]. However, the important consequence of the abstractions advocated by Galileo is the role that ingenuity and insight have in the resolution phase of scientific explanation. Conjectures and hypotheses about such abstractions cannot be obtained from inductive methods of enumeration, agreement, or difference. In the transition from reality to the ideal, the scientist, exemplified by Galilean thought experiments, must use creativity and imagination as the building blocks of idealization.

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62 Galileo Galilei, *Two New Sciences,*

63 Galileo also made other claims that contradicted known patterns which seem to indicate that he thought about the way the world should behave. For example he claimed that the swing of the pendulum was independent of its amplitude for large angles.

Galileo also rejected Aristotelian teleological explanation that every object has a natural place, as part of legitimate science. He demonstrated the power of the thought experiment to challenge the Aristotelian belief that the natural tendency of a body in motion was towards the centre of the earth. He wondered what would happen to an object which was dropped down a well which was part of a hole bored through the earth. The object must be initially accelerated towards the centre but what happens when it gets there? Does it stop? Will it continue in motion suddenly moving upwards, and if so, is this motion natural?

While Galileo challenged the fundamental ideals of the Aristotelian view, Francis Bacon challenged the methods of Aristotle. He criticized the uncritical reception of Aristotle's philosophy as an Idol of the Theater (a received dogma) and claimed that Aristotelians practiced uncritical collection of data, jumped swiftly to the most general principles, relied heavily on induction by enumeration, overemphasizing confirming instances. Bacon insisted that the purposes of science were to control nature and benefit humankind. He believed that Aristotle's philosophy to understand nature, and therefore man's place in nature, would not lead to new works to benefit humankind. He sought to "kindle a light in nature and restore science to its proper place of servant to the will of man, rather than merely delight to his intellect".[64]

Bacon's methods included gradual, progressive inductions from observations to

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64 quoted from Blake et al., *Theories of Scientific Method, The Renaissance through the Nineteenth Century*, originally from the Prooemium to the Great Instauration, in the edition by James Spelding, Robert Leslie Ellis, and Douglas Denon Heath, *The Works of Francis Bacon* (London: Longman and Co., 1857 - 59).

forms[65]. He advocated for experimental science, the systematic, careful, unbiased collection of facts and he emphasized the value of scientific instruments in this role. On experimentation he wrote, "For the subtlety of experiment is far greater than that of the sense itself, even when assisted by exquisite instruments". [66] Bacon also derided Aristotle's syllogism as useless and his induction by enumeration as childish. He proposed a form of induction that "must analyze nature by proper rejections and exclusions; and then after a sufficient number of negatives, come to a conclusion on the affirmative instances".[67] The consequences of Bacon's inductions were to be regarded as hypotheses that must in turn be tested with the facts. Bacon did not reject deductive reasoning outright but he argued that deductive reasoning could only be of value if the originating premise had sufficient inductive underpinnings. Bacon organized his data in detailed tables which accounted for the essence and presence of the phenomena in question, its' deviation or absence in proximity, and for degrees of comparison.

Bacon recognized that simple inspection of the data would not likely reveal any laws of nature so he outlined the importance of 27 *prerogative instances*[68] such as solitary instances, striking instances, bordering instances, and the instance of the fingerpost. On theory acceptance, Bacon introduced the notion of a critical experiment

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65 F. Bacon, Novum Organum, II, Aphorism XVII. Bacon stated that by forms "I mean nothing more than those laws and determinations of absolute actuality, which govern and constitute any simple nature, as heat, light, weight". By laws, Bacon did not mean mathematical relations as we might think today.

66 Francis Bacon, from the *"Plan of Instauration"*, Part III, in Blake, p 54.

67 Francis Bacon, *Novum Organum*, I, 105, in Blake p 53

68 For an explanation of all 27 instances the reader is directed to Blake, p 57.

with the "Instance of the Fingerpost" which he describes as "An instance where only one of the two rival supposed characters of the form is found conjoined with the nature investigated excludes the possibility of the other's belonging to the form of that nature". [69] In such a case, an instance was critical if it was inconsistent with all premises except one. As Grosseteste points out, such an inductive view of science suggests that scientific theories and laws are only more or less probable[70]. However, a science which is only probable did not rest easy with some philosophers.

Rene Descartes expressed a discontent with a science that was merely probable. He emphasized the role of hypothesis, and he maintained the view that scientific progress was a deductive one. He wanted certainty of the kind found in mathematical proof. That is, laws of nature were not born of empirical origins but were derived deductively from self-evident principles. For example, Descartes claimed that God created the world by setting the matter of the universe in motion all at once. Thus, he concluded that motion must be conserved perpetually or it would run down like a wound up clock. From this fundamental principle Descartes derived his laws of inertia from which he could formulate a set of rules for the behaviour of all objects in motion.[71]

In this way, Descartes inverted Bacon's mode of thinking about science. Although he doubted that laws of nature could be derived from a collection and

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69 found in Blake, p 61, Novum Organum II, 37.

70 Crombie, Medieval and Early Modern Science, p 15. from book 2, chapter 5 of Grosseteste's commentary on the *Posterior Analytics.*

71 Descartes rules, like his rules of impact, did not always conform to, and often contradicted real world motion, see Losee, p 78 for more detail.

comparison of a series of observations he did acknowledge that observation would play a role in science suggesting that laws "require a datum to which they are applied and which they interpret, but which they accept without themselves being able to justify.[72]

Descartes' mode of thinking was insufficient for Isaac Newton. In opposition to the Cartesian method of science, Newton re-affirmed Aristotle's method of induction-deduction which he called analysis and synthesis. In his treatise on Opticks, Newton claimed that

> "although arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions, yet it is the best way of arguing which the Nature of Things admits of".[73]

Newton sharpened his method of analysis and synthesis with two additional qualities. First, he insisted that consequences deduced in the synthesis stage be experimentally confirmed and secondly, he advocated that any deduced consequences should extend beyond the original deductions. For example, after Newton concluded inductively that sunlight was made up of rays with different refractive properties he applied his method of synthesis to extend these consequences to a new test[74]. If he passed a light of a certain colour through a prism then it should not split into any other colours and it should refract at the angle characteristic of that colour. Newton then confirmed this property in a

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72 Gilson, Texte et commentaire, p 272.

73 Isaac Newton, *Opticks*, New York: Dover Publications, 1952), p 404

74 Losee suggests this is an inductive leap of sorts as Newton did not just suggest that all prisms behaved this way but he theorized about the nature of light itself. For complete details see Isaac Newton, *Opticks,* p 45 - 48.

simple test using two prisms.

Newton's claim that he actually adhered to his method of Analysis and Synthesis to develop his laws of motion is more problematic. His first law of inertia concerns the behaviour of objects which experience no forces. Since no such objects exist, the law of inertia is more of an abstraction from the motion of real bodies rather than the result of real world observations. Other elements of Newton's work were also abstractions, for example Newton's notion of time and space. Losee[75] contends that Newton's used an axiomatic method in the *Principia.*

> His explicit discussion of this problem of correspondence indicates that he followed an axiomatic method in the Principia rather than the inductive method of Analysis"

According to Losee, Newton's axiomatic method consisted of three stages:

1. Formulation of an axiom system,
2. A procedure for correlating theorems of the axiom system with observations,
3. Confirmation of the axiom system with phenomena.

Newton recognized that the degree of agreement can be increased by progressive modifications of the original assumptions. He included a feedback loop[76] which maintained that the laws of nature endured a contingent status that may be revised with the accumulation of new evidence.

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75 Losee, J. p 90

76 L. Bernhard Cohen, *The Newtonian revolution*, Cambridge: Cambridge University Press, 1980, p 52 ff

Newton's synthesized an understanding of the laws of force and motion for the first time revolutionizing our view of the world and few questioned his ideas. However, George Berkeley, a contemporary of Newton, resurrected the conflicting views of the realist and the instrumentalist and was one of the first philosophers to criticize Newton's philosophy of science. Even though Newton cautioned about speculating on the nature of forces, Berkeley claimed that Newton spoke of force as something more than a term in an equation. He emphasized that mathematical constructions, like forces or epicycles, were useful in calculating data but warned it was a mistake to attribute a real existence to them. Berkeley's strict instrumentalist view holds that there are only two kinds of entities, ideas and minds. To be is to perceive or be perceived, and he held no distinction between the primary and secondary qualities of Galileo, Descarte, and Newton.

19th Century Science

Aristotle's inductive-deductive approach to science was again revisited in the 19th century by many historians and philosophers of science. Notably, John Herschel (1792 - 1871) published *A Preliminary Discourse on the Study of Natural Philosophy* which included an analysis of the role of hypothesis, theory and experiment in science. In his discourse Herschel argued that empirical verification was the most important consideration in the evaluation of good scientific theories. Like Bacon, Herschel felt that some confirmations were more important than others and he claimed that good theories survive a "severe test". He accepted Foucault's calculation of the speed of light in water as a critical experiment which favored Huygen's wave model over the corpuscular model of Newton. Of course, as proponents of the value of critical experiment often do, Herschel ignored the fact that other interpretations for light could exist. Years later, in 1954, Duhem[77] addressed the issue of a crucial experiment and argued that an experiment could only be "crucial" if it eliminated every possible set of explanations except one. Consequently, he insisted that there are no such experiments.

Herschel began to discuss laws of nature and he considered laws of nature to be both correlations of properties and sequences of events. For example, Boyle's law was a correlation of the variation in the pressure of a gas and the volume of the gas while a sequence of events would consist of the successive displacements of an object in free fall. Herschel also recognized that laws were held to constraints such as the requirement of a constant temperature for Boyles law. Following the discovery of laws, theories were required to provide explanations of these laws. Herschel claimed that theories were developed through additional inductive generalizations or through the development of hypotheses. In the latter, a creative imagination was a key component and Herschel was impressed with imaginative theories like Ampere's explanation of electromagnetism[78].

John Stuart Mill (1806 -1873) was a strong advocate for inductive methodology as the means to discover scientific laws. Mill extended the methods of Duns Scotus and Ockam to include four inductive procedures:

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77 Duhem, Pierre (1954), Physical Theory and Experiment, in Philosophy of Science, The Central Issues. Eds. Martine Curd and J.A. Cover

78 Ampere explained the attraction and repulsion of magnets with eddy currents.

Mill's Methods of Induction

1. Agreement.
2. Difference.
3. Concomitant variations.
4. Residues.

Table 4: Concomitant Variation

Case	Cause	Effect
1	$A^{+}BC$	e^{+}
2	$A^{-}BC$	e^{-}
3	$A^{o}BC$	e^{o}

Table 5: Residues

Case	Cause	Effect
1	ABC	def
2	B	e
3	C	f

A and d are causally related.

In the case of concomitant variations, if variations in the cause A result in the same variations in the effect e then A and e are causally related (table 4). In the method of residues if we can establish a causal relationship between two of three factors then the third factor must also be causally related (table 5).

In the 19th century, another early idea of the Greeks garnered a considerable amount of attention as many scientists were beginning to focus on atomism as the fundamental underlying structure of matter. However, as with the early Greeks, not all were convinced. The famous physicist Ernest Mach, like Berkeley, refused to posit a realm of reality. He held that theories about entities (like atoms) may be useful for the description of certain phenomena but that this provided no evidence for the existence of atoms. The instrumentalist position was also advocated by Poincare who advanced a view that scientific laws merely specify the meaning of a scientific concept. That is, they were conventions, and laws, like Newton's 2nd law of dynamics, render conventional definitions of concepts like force or mass such that no empirical evidence can be found that might contradict the definition.

By the end of the 19th century, new philosophies of science based on positivism began to take hold and started to proliferate as public education expanded rapidly in the Americas. Positivism asserted that knowledge was based on sense experience and observation, and experiments guided inquiry. The method of science was inductive and general laws were established on the basis of observation. Although a positivist philosophy was fuelling the philosophical discussions of this period it was not without critics. Jevons was critical of such Baconian practices and described in his book, *Principles of Science*, the methods of Newton, who "proceeded to use his imagination and test his theories by experiment" (as quoted in Pearson, p. 34). Karl Pearson (1892), a strong adherent of empirical techniques, acknowledged the controversy concerning strict empirical methods. However, he dismissed Jevons and claimed that history has shown that the collection of facts always preceded scientific theory.

The 20th Century

By the beginning of the 20th century a great deal of the debate surrounding the nature of science was taken up by philosophers of science who often did not practice science. The problem with current philosophy of science is that it is increasingly specialized (Elfin, Stuart, & Reisch, 1999) and most of this debate stretches out of reach of the secondary school student. However, several significant arguments concerning the nature of science are presented here for their importance to the discussions of the 20th century, as important reflections for teachers of science, and for their potential inclusion in discussions concerning the nature of science in high school classrooms. These arguments include the ideas of Karl Popper, Thomas Kuhn, and Imre Lakatos concerning demarcation of science and pseudoscience, their ideas on theory choice, and the views of Hillary Putnam, Rom Harré and Ian Hacking on the realism of scientific theories and theoretical entities such as electrons.

In his seminal piece, *Conjectures and Refutations,* Karl Popper (1963) confronted the new theories[79] of the 20th century as he wanted to demarcate between science and pseudoscience. He compared the theories of Einstein with the theories of Marx, Adler, and Freud. He concluded that it is easy to obtain confirmations of theories but confirmations should only count if they risk falsification. That is, he claimed that every genuine test of a theory is an attempt to falsify it. He argued that pseudoscience made vague predictions that could hardly fail while scientific theories make bold predictions which may not be confirmed until many years after the fact and, if shown to be false, cause you to give up the theory (eg. Einstein's bending of light or Copernicus' phases of Venus). In this way science progress as new and better theories survive risky verifications.

Thomas Kuhn (1962) sought to show that science progresses mainly during long periods of "normal science" whose practitioners follow a common paradigm.

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79 Popper was part of the intellectual circle in Vienna at the beginning of the 20th century and was influenced by the theories of Karl Marx, Freud's psycho-analysis and Adler's individual psychology. He worked with Adler for a while and was always perplexed at how Adler could explain any encounter with his theory.

Periodically, through scientific revolutions, this paradigm is overthrown (eg Copernicus' heliocentric system replaces Ptolemy's geocentric system). Kuhn compares scientific revolutions to political revolutions where existing institutions (paradigms) cease to deal adequately with current problems. New paradigms are presented and scientists are divided into two groups, each group using its own paradigm to argue the paradigm's defense. As a new paradigm emerges, the new normal scientific tradition is incommensurable with the previous. That is, the same terms often mean completely different things (eg. mass in Newton's and in Einstein's physics).

Kuhn argued that Popper's ideas only accounted for revolutionary science (which is rare). He suggested that it was the period of normal science which demarcated between science and pseudoscience and he described how astrology could be considered a science using a Popperian interpretation[80]. However, Kuhn argues that it is actually the lack of puzzles to solve (current problems in normal science) that causes astrology to be a pseudoscience.

Kuhn[81] also undertook to define how scientists decide on their theories. He claimed that the five characteristics of good scientific theories were: accuracy, consistency, scope, simplicity, and fruitfulness. First, he claimed that a theory should be in agreement with existing observations and experiments. A theory should be both internally and externally consistent with other theories and its scope should extend

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80 See Kuhn's criticism in Logic of Discovery or Psychology of Research?

81 From Kuh, T. Objectivity, Value Judgement, and Theory Choice in The Essential Tension.

beyond what it was designed to explain. A theory should also be simple and fruitful, that is, it should generate questions and lead to a robust research program. Kuhn also maintained that theory choice depended on individual biography and personality. Thus, any criteria for theory choice are value laden, and as such, they are subjective.

Imre Lakatos (1977)[82] pleaded that we take the problems of pseudoscience seriously. He asserted that we should not abandon theories because the facts contradict the theory. Lakatos first outlined his idea of research programs. Every research program has a "hard core" of ideas and theories which are at the center of the program. Surrounding this hard core is a set of auxiliary hypotheses which protect the hard core. The outer belt of hypotheses are flexible and can change as the program encounters new problems. For Lakatos, the demarcation of science is a progressive versus a degenerating research program. A progressive research program predicts novel facts. When theory lags behind the facts we dealing with a degenerating research program.

Another central debate of 20th century philosophy of science re-examines the instrumental versus realism dichotomy. Hilary Putnam in 1978 argued that the predictive success of science could only be accounted for by a realist interpretation of our theories. However, this argument proved problematic for most philosophers who resurrected Hume's position that no amount of confirmations can guarantee the success of any future tests. Thus, the realist's could only reference "approximate truth" or "progress toward the truth", both slippery arguments at best for the philosopher. However, although it was

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82 Written in early 1973 as a radio lecture broadcast by the Open Unversity.

difficult to argue the case for the truth of our scientific theories, the argument is more persuasive for the truth of the entities postulated by our theories. Rom Harré (1986) outlined three realms of reality for claims of entity realism. The first realm asserts the existence of observable object such as the planets, the oceans, or the internal organs of the body. The second realm concerns claims made for "objects of possible experience" which are accessible through the amplification of human senses. For example, Harvey's theory of the human circulatory system postulated connections between the arteries and veins. Eventually, microscopes permitted the discovery of capillaries, entities only accessible through an extension of our senses. The third realm of existence are entities which are not accessible to our senses even through extreme amplification. Objects like neutrinos, quarks, and electrons fall into the category of realm three. Ian Hacking (1982), a Canadian philosopher, argued that electrons were real, not because they are posited by a successful theory, but because we can manipulate them to produce new phenomena. In Hacking's words, electrons are real because "we can spray them".

Science today is presented in its' "final form" (Duschl, 1985) with a focus on what we know as opposed to how we know it. Even educators see science as an established body of knowledge which requires no justification (Gallagher, 1992). In this thesis, I am arguing that understanding NOS helps us think more clearly about science and formulate arguments to address such questions as "how do we know" and "what are the good reasons to believe". One of my intentions for the preceding discussion of the history of NOS is to examine the recurring themes in NOS in the history of science. Several aspects emerge from this discussion which relate to science education.

Aristotle presented a view of scientific inquiry as an inductive-deductive cycle fostering an ongoing dialogue with nature to produce explanations of natural phenomena. The processes of this methodology included observation, inference and several characteristics of good argumentation. The syllogism, methods of agreement and difference, and later falsification, outline some aspects of NOS which might be useful promoting a more philosophically valid curriculum. For example, in building a model of electricity in the MB Senior 1 science unit, students construct and investigate electrostatic phenomena using a pieplate electrophorous (figure 8). Initially, they are able to determine, after rubbing the styrofoam plate, that the charge on the bottom plate is negative. After they place the aluminum plate on top of the styrofoam the foil bit indicates a charge on the aluminum pieplate. Students incorrectly conclude that the negative charge has transferred from the styrofoam to the aluminum plate by conduction. If we lift the aluminum plate, the foil bit indicates that the aluminum plate has a neutral charge. In their deliberations, students are encouraged to use a *modus tollens* argument as follows:

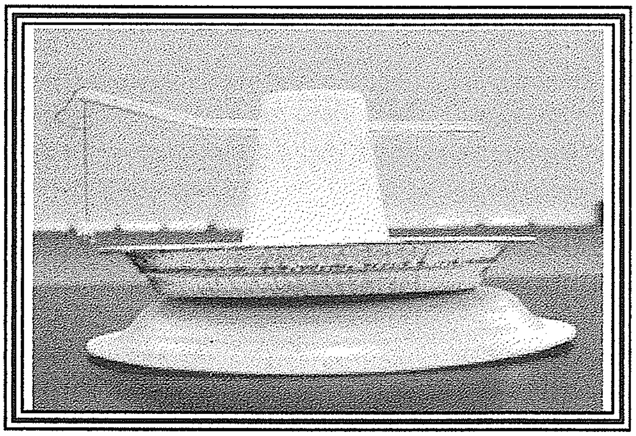

Figure 8 - Pie-plate Electrophorous

- If a negative charge transfers from the styrofoam to the aluminum plate, then the aluminum plate will be negatively charged when it is lifted.

- The aluminum plate is not negatively charged when it is lifted.
- Therefore, the negative charge did not transfer from the styrofoam to the aluminum.

Next, students are led to consider alternative explanations which do not contradict the argument. In this way, students develop reasons to believe which they back up with supporting arguments.

An understanding of deductive reasoning and the deliberations of early philosophers such as Descartes and Herschel on hypothesis, theories, and laws can also be used to develop a higher order of thinking skills supported by many educators (Lawson, 1982). For example, research by the Mazur Group at Harvard University shows improvement in student performance when students deduce the outcome of a demonstration before seeing it[83]. Although more research is needed in this area, this mode of thinking is certainly more reflective than pure inductive practices.

Another recurring theme stemming from scientific inquiry concerns how science progresses. An evolutionary model as outlined by Bacon, which suggests that our knowledge accumulates with careful observation and unbiased investigations, is contrasted with the revolutionary advances proposed by Thomas Kuhn. In a related process, students could be challenged to consider the nature of a good explanation as described in the history of NOS through the ideas of parsimony and Kuhn's five characteristics of a good scientific theory. This reflection, necessarily forces us to

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83 Mazur, Eric as reported at mazur-www.harvard.edu/education/demo.html

consider the subjective and cultural influences of society as science, through its' history, becomes a more humanistic discipline. Another of my intentions for the preceding discussion of the history of NOS is to establish a basis for the science educator to more fully understand the contentious issues in NOS. These contentious issues are not only important to the educator from a scientific perspective but also from a pedagogical perspective. Two of the critical ideas in science education in the 20^{th} century, inquiry and constructivism, are closely linked to understanding NOS and teaching NOS. Inquiry has been criticized for many years for promoting a naive understanding of NOS (Harris and Taylor, 1983). Additionally, Michael Mathews (1994) argues that the relationship between constructivism and NOS is also a historical one:

> "Discussion of constructivism leads naturally into discussion of a debate that has echoed through the history of science, and that bears significantly upon the nature of science: namely that between realists and empiricists". (p.161)

Further, Mathews contends that the arguments of constructivism "are so central to science that only a truncated science education can ignore it". Therefore, in order to develop a more complete and relevant understanding of NOS, it is essential that we examine the relationship between NOS and the ideas of inquiry and constructivism in the 20^{th} century. Thus, in the next chapter, I begin to examine the influences of NOS in the science education community.

Chapter III

The Nature of Science in 20th Century Science Education

Introduction

There are several aspects of the history of NOS that influenced prominent philosophies of education. My intention in the next few pages is to outline these connections and their role in the development of science education in the 20th century.

By the end of the 19th century new philosophies of science, based on empiricism, began to take hold. In 1893, L. L. Conant, a leading Harvard educator promoting the use of experimental methods in high school, argued that

> "Empiricism is the watchword of today . . . the high school or academy which is not well equipped with laboratories is not looked upon as "progressive," as "up to the time."[84]

In other words, not to adopt such a perspective implied a less progressive education. As public education expanded rapidly at the beginning of the 20th century, it started to exert tremendous influence on North American society. Several critics debated the nature of science in science education and an ardent commentary soon emerged in the writings of John Dewey[85]. Dewey was a Professor of Philosophy at Columbia

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84 L.L. Conant, School Review, I, 3, 211.

85 Dewey was a prolific writer. For a sample see, Science 31, 787, 121 - 127.

University who had some exposure to natural sciences in his undergraduate studies. He had high school teaching experience and a keen interest in education. Dewey reasoned that the psychological processes of learning should guide instructional techniques in education. He espoused the benefits of individual experiences through the active engagement of the learner with their environment. He advocated the importance of scientific method which he interpreted broadly as the processes through which we acquire scientific knowledge. For Dewey, it was not enough to fill students through "*information hoppers*" with an abundance of scientific facts. An individual's experiences were the raw materials the learner used to formulate meanings. Dewey suggested that

> "Only by taking a hand in the making of knowledge, by transferring guess and opinion into belief authorized by inquiry, does one ever get a knowledge of the method of knowing. Because participation in the making of knowledge has been scant, because of the reliance on the efficacy of acquaintance with certain kinds of facts has been current, science has not accomplished in education what was predicted for it." (p 121).

Dewey criticized current education practices that treated science as subject matter and he claimed that science curriculum was "breaking down because of its sheer mass." However, his rationale for practical work went beyond the common notion that the lecture and textbook were not sufficient as teaching strategies.

> "Many a student has acquired dexterity and skill in laboratory methods without it every occurring to him that they have anything to do with constructing beliefs that are alone worthy of the title of knowledge." (p 124)

Dewey also insisted that science must have something to contribute to social and moral ideals, the democratic process, and freedom. "Actively to participate in the making of knowledge is the highest prerogative of man and the only warrant of his freedom." Schools should be not just be laboratories but "laboratories of knowledge-making." Although his philosophy and his teachings perhaps led to a more humane and flexible school system, school science instruction did not embrace his ideas relating learning theory and practical work for many years to come.

If empiricism was the watchword at the turn of the century then "inquiry" was most certainly the watchword in the post-Sputnik race for technological supremacy. The curricular reforms of the 1960's were heralded as a significant break from the past. Shymanksy (1983) marked a clear delineation between "traditional" curriculum and the new "inquiry-based" paradigms of instruction. He defined new curricula as:

a) developed after 1955 (with either public or private funds).
b) emphasized the nature, structure, and processes of science.
c) integrated laboratory activities into the core of the instruction.
d) emphasized higher cognitive skills and an appreciation of science.

And he represented traditional curriculum as:

a) developed or patterned after a program developed prior to 1955.
b) emphasized knowledge of scientific facts, laws, theories and applications.
c) used laboratory activities as verification exercises or as lesson supplements.

Inquiry-based learning focussed on science process skills, it emphasized hands-on activities favouring observation, classifying, measurement, and controlled experimentation using independent and dependent variables. Inquiry was intended to promote thinking and reasoning skills as students participated in authentic science activities. However, students were never challenged to employ the skills that they had learned by developing and evaluating their own ideas. The problems of inquiry-based learning led educators to critically appraise many principles and practices of inquiry-based learning. Welch, Klopfer, Aikenhead, and Robinson (1981) suggested that "the values associated with speculative, critical thinking were often ignored and sometimes ridiculed" and that "the optimistic expectations for students becoming inquirers have seldom been fulfilled". Mathews (1994) argued that teachers' unfamiliarity with the history and philosophy of science prevented teachers from avoiding the naive claims of inquiry and discovery learning such as:

> "that scientific method is inductive, that observation does not depend upon conceptual understanding, and that messing about with real objects can reveal the structure of the scientific theories that apply to those objects" (p 28).

Harris and Taylor (1983) suggested that inductive methods of inquiry had become fused with a progressive view of education and they summarized the philosophical problems associated with inquiry-based instruction. They claimed that inquiry, or "discovery" learning, favoured abstraction and the confirmation of theories. They argued that abstraction implied a view that meaning is embedded in, and can be drawn out of objects, while verification of existing theories was dogmatic and left no room for alternative explanations. Further, Harris and Taylor outlined that a curriculum which uses inductive methods extensively, like PSSC physics, describes the world as governed by universal, fixed and unchanging laws. Therefore, this form of curriculum suggested that the job of the scientist was to uncover nature's laws. As a result, this naive view of science led to a set of illusions about the scientific enterprise, including the portrayal of experimentation as a definable scientific method preceding directly from observation to theory. It was also implied that this specifiable method can be taught and depicted as a series of steps in the form of hypothesis, observation, measurement, and generalisation.

After many years, the research on the success of inquiry-based methods was still inconclusive and many educators (Driver & Oldham, 1986; Harris & Taylor, 1983) had shown that its' philosophy was inconsistent with prevailing views. Consequently, educational researchers began to concentrate their efforts on cognitive issues and the analysis of the cognitive domain emerged in the 1980's as the dominant type of research in science education (Yager, 1992). Many science educators (Driver & Oldham, Osborne & Wittrock 1983) began to propose that a constructivist epistemology should replace the inductive mode of inquiry-based learning. Constructivist learning theories, grounded in the work of Piaget, depicted conceptual change as a process of assimilation whereby a student used existing concepts to understand new phenomena. If existing concepts were incapable of dealing with some new situation then the learner must revise their conceptual structure in a process called accommodation. An essential premise of constructivist-based learning profiles the learner as an active participant in the construction of his or her own knowledge. Students did not come to school "*tabula* *rasa*," that is, as a blank slate, an empty vessel to be filled with predetermined scientific knowledge. The learner can neither passively receive information, nor can we simply download words and concepts to the learner. Discourse and dialogue, rooted in the works of Vygotsky (1962) were considered to be essential aspects of a constructivist learning environment. Vygotsky also proposed that cognitive development was shaped by the learner's social experiences that guided the formation of concepts.

A more radical constructivist view suggested that there was no universal reality. That is, we do not find truth about the real world but each individual constructs his or her own view from their own experiences. Von Glaserfeld (1995) explains,

> "To the constructivist, concepts, models, theories, and so on are viable if they prove adequate in the contexts in which they were created" (p.7).

In this view, science is an activity of constructing relationships and patterns in an instrumental manner whereby entities and models are useful constructs that help explain our experiences. In the more radical view of constructivism there exists a uniquely constructed reality for each individual. In this view, the notion of viability replaces the concept of truth. In contrast, a realist maintains that the relationships, patterns and entities[86] exist independent of the learner (Wheatley, 1991). Thus, in terms of the nature of science and science education, radical constructivism challenges the realist's position and can be viewed as an extension of the anti-realist/realist controversy (Mathews, 1994)

These controversies have been highlighted throughout the history of NOS in the

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[86] such as electrons

confrontations of Aristotle's and Ptolemy's universe, the positions of Galileo and Cardinal Bellarmine on the Copernican system, the views of Newton and Berkley on force, and the atomists and Mach's belief in the existence of fundamental particles of matter. In any case, understanding the classical realism versus anti-realism debate leads to a greater understanding of the spectrum of philosophies in science education. Thus, teaching and understanding the nature of science becomes not only important from a scientific point of view but it leads to a greater understanding of other perspectives as well. In light of these contentious issues surrounding NOS and pedagogy, many educators have wondered how we might build a consensus on the aspects of NOS that might be accessible to high school students.

Building a Consensus for Teaching NOS

McComas and Olson (1999) examined eight recent curriculum reforms, including the Pan-Canadian frameworks (CMEC, 1997) for their inclusion and depiction of NOS, and they believe that "there is clearly a consensus regarding the nature of science issues that should inform science education" (p. 556). Common themes which they identified from the documents include that science is an attempt to explain phenomena, that science is tentative, creative, part of a social, cultural, and historical tradition, and science relies on empirical evidence. They concluded that NOS is a "hybrid domain informed primarily by descriptive scholarship from a variety of disciplines", specifically philosophy, history, sociology, and psychology.

Felske, Chiappetta, and Kemper (2001) argued that through a careful inspection of the literature a common thread throughout the numerous curriculum reform movements has been several aspects of NOS. Felske et al. collated 21 statements on various aspects of NOS[87] from Benchmarks (AAAS, 1993) and the Standards (NRC, 1996) documents and using a numbered Likert scale surveyed five NOS "experts" to determine if they could arrive at a consensus[88] on the NOS statements. After the first round a "consensus" was reached on 18 of the 21 statements. After two more rounds in which the respondents could suggest word changes and anonymously reply to the other experts stated positions, consensus was reached on 20 out of 21 NOS statements. Fenkse et al. boldly proclaimed in the title of their report, "at last some consensus on the nature of science for science education".

There are several significant weaknesses in this study that counsels us to doubt the declared consensus. First, the statements adopted in the evaluation were taken from two curriculum reform documents[89] which themselves are consensus documents. One could surmise that reaching consensus on statements already vetted by "experts" might be considerably easier than finding agreement on a set of statements submitted by an independent body. Secondly, the so-called consensus reaches out to only 5 NOS "experts", from the science education field only, and ignores any of the concerns which

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87 Typical NOS questions would be "Although all scientific ideas are tentative and subject to change, there is much experimental and observational confirmation for most major ideas in science (Benchmarks p. 5). For a complete list of the 21 questions see Fenkse et al. p 22.

88 Fenske et al. use an agreement criteria of >80% as determined from a four step disagree/agree Likert scale with no neutral response.

89 Benchmarks (AAAS, 1992) and Standards (NRC, 1996)

might be expressed by historians and philosophers of science. Finally, the study actually reveals that consensus is not achieved on all questions. The single question for which consensus is not achieved highlights a controversy for which we will never reach consensus. This questions reads, "The historical perspective of scientific explanations demonstrates how scientific knowledge changes by evolving over time, almost always building on earlier knowledge" (Benchmarks, p 4). The "agree" and "disagree" responses from the experts could not be resolved after three rounds of discussion, and one respondent supported both positions somewhat agreeing and disagreeing at the same time! In terms of understanding this question, the issue is not whether we can reach a consensus on it but rather can we identify and understand the difference in views which are reflected by a Kuhnian revolution versus the evolution of scientific knowledge.

Others have also challenged the educators' notion of consensus asserting that agreement on NOS is not universal. Alters (1997) takes issue with the basic tenets of NOS as outlined by Lederman (1983) and criticizes that the basis for these tenets "is almost universally absent from the literature". Moreover, Alters insists that we must call on philosophers of science to examine the basic tenets of NOS as explicated by educators and to provide some guidance in establishing a more accurate view of NOS. Alters is not proposing a single view of NOS, he claims that

> "This is not to suggest that a consensus of philosophers of science be used to construct one set of basics tenets, but that some scheme might be developed wherein multiple sets of views from the philosophers could be organized into useful accurate criteria" (p 43).

Alters brings to bear two important criticisms of NOS as viewed by science educators. First, the stance maintained in many of the NOS assessment instruments and by their associated supporters is that one view of NOS is preferred[90]. However, Alters' view that philosophers of science could provide a scheme of multiple criteria that might form a more accurate basis for NOS is not convincing. In his own research he reveals "a minimum of 11 fundamental philosophy of space positions"[91] that are held by philosophers of science today. Clearly, such an array of positions are untenable as instructional outcomes in a science classroom. While I can agree with his conclusion that there is no one agreed upon NOS position, I do believe that the controversies can be captured much more succinctly. The question is not whether the philosophers of science agree on the basic tenets of NOS, history has shown us that they do not, nor will they ever agree. The question is "what are the competing views of NOS and what elements of the controversy should be taught in science education?" To begin to answer this question, educators must first address Alters next criticism.

Alters alerts us to the fact that "the basis for arrival at the tenets, whether in quantitative or qualitative instrumentation and related reporting, is almost universally absent from the literature". Indeed Alters cites fair criticism with respect to accounting for and justifying the tenets of NOS as outlined in the literature and in the curriculum reform documents. For example, Lederman's principles of NOS have been presented as pre-justified tenets of the nature of science for which no basis has been established. One

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90 Typically today that view is one of Instrumentalism, see Lederman (1998)

91 Alters reports that only the philosophers' view of the structure of space correlated to their stated philosophy of science represented by a priorism, conventionalism, positivism, and realism.

way of providing for this basis is through an understanding of the history of NOS as presented in the preceding pages.

From a different point of view, Ray (1991) also cautions against a consensus view of NOS and he warns us of the danger of "those educationists who seize on the latest philosophical trend and try to turn it into a universal panacea" (p. 88). He recounts several philosophical ideas which have influenced science teachers including positivism, falsificationism, problem-solving, and model building. He argues that the Nuffield science program in the U.K. promotes an instrumental view emphasizing observation and experimentation at the expense of theorizing, and he contends that many have been won over by Popper's ideas on falsification in spite of convincing attacks on his ideas. Additionally, he suggests Kuhn's puzzle-solving period of normal science encouraged the problem solving popularity in the early 1980's, and Hesse's (1974) work on the importance of models, metaphors and analogies are apparent in Driver's (1987) work on conceptual development. Even though he is a philosopher of science with strong convictions, Ray does not so much take issue with these particular NOS influences but with the fact that educators "fail to convey to their audiences the fact that there are numerous and sometimes fundamental disagreements about science"(p 91). To this aim, he advocates discussing the benefits and limitations of diverse NOS views by emphasizing historical and contemporary case studies. We should also note that Ray does not accept an "anything goes" attitude. He cautions that we should embrace "neither such single-minded conservatism, nor a free-for-all anarchy, but an informed and thoughtful liberal attitude towards the philosophical foundations of science education"(p93).

So, while we must continue to remember that our concern with teaching NOS remains within the K-12 realm, as educators, we must also be prepared to examine the more contentious aspects of NOS and ask ourselves how, and when, we might address these issues in the secondary classroom.

Contentious Issues in NOS

The history of NOS revealed many examples of the early debates concerning the nature of science and recurring themes in the nature of science began to emerge. These themes included the demarcation between science and other modes of thought, the nature of scientific method, the criteria for judging scientific explanation and scientific theories, the progress of science, and the cognitive status of scientific laws and the entities that our theories postulated. Several issues emerged from these NOS themes, including some consensus and some disagreements.

It seems to me that we can divide these aspects of NOS into three separate categories. First, we have NOS tenets for which we have significant consensus throughout the education, historical, and philosophical domains. Second, there are tenets that we have consensus for at an elementary level of understanding, but which have some aspects which remain contentious at other levels of understanding, and third, there are tenets which are contentious and perhaps always will be.

First, there is significant agreement across disciplines that science is rational and that we seek to find theories to describe and explain the physical universe in a simple, yet comprehensive manner. Furthermore, science and scientific knowledge remains tentative. This fundamental tenet of NOS describes science as a dynamic enterprise which is continually subject to change (Elfin et al. 1999; Lederman et al., 2001; McComas & Olson, 1999) In spite of this tentative nature of science, our best theories are extremely robust and we literally "bet our lives" on them.

There also appears to be significant agreement that there is no one specifiable scientific method of the kind often depicted in science textbooks and that human creativity and imagination play an important role in the development of scientific knowledge. There also seems to be a great deal of agreement that science can be subjective and the scientist is influenced by his or her culture and background. Consequently a scientists' commitments, beliefs, social, and cultural influences influence their work. However, while such a consensus seems to exist on these latter two issues, we must acknowledge that even though currently out of favour, from time to time history has shown us that the contrary view can be quite seductive (for example: Bacon and Pearson). That is, that science can only progress at the hands of an objective, unbiased observer of nature who follows a strict set of guidelines.

In the second group we find that most parties agree on the nature of observation and inference at one level, at least for early learners. That is, observation is based on sense data and inference is the meaning that we assign to this data. Additionally, most are in agreement that our observations are theory dependent and that our expectations influence our observations. On a more sophisticated level, the cognitive status of our observations and the instruments that we use represent more problematic issues. These more difficult issues surrounding the nature of observations are better left to an appropriate time but I don't necessarily believe that we need to sidestep the anti-realist/realist debate on the ontological status of our observations. In fact, I believe students find it interesting.

Also, in this second group, there is a general agreement that the aims of science are to acquire knowledge about the physical world. However, the motivation for these aims is much more divisive, do we acquire knowledge for the sake of knowledge (Aristotelian view) or do we acquire the knowledge in order to control nature? (Baconian view). In 1975, Smolicz and Nunan stated that science curriculum assumed that the goals of science were to control nature and consequently science education should advance the ability of science and technology to achieve these goals. Indeed, it seems that over 25 years later, the Ontario science curriculum advocates this position over the more liberal Aristotelian view. Maxwell (1984) claimed that this philosophy of control dissociates science from a concern for human values and Hodson (1990) argued that the use of knowledge to alter and control events must be extended to the pursuit of wisdom and the responsible use of science and technology. A growing literature with respect to a multicultural and feminist perspectives (Bentley and Watts, 1986; Hodson, 1988; Longino, 1989), and, a concern for the environment and the role of social responsibility in science (Maxwell, 1984) indicates that the motivations behind the aims of science will continue to fuel this debate for many years to come. However, most of these arguments are only accessible to a more advanced study of philosophy and science.

Another area of initial agreement relates to the questions of science. There is a general consensus that the questions of science differ from the questions of other ways of knowing such as religion. However, where and how we draw this line remains contentious and has changed throughout history. While some philosophers still maintain that there is no distinction between science and non-science, most philosophers and educators try to eliminate certain questions (like astrology or creationism) from the realm of science. Smith and Scharmann (1999) suggest that we should not attempt to mark exact boundaries between science and non-science but that we should begin to ask questions such as "what are the characteristics of the field that make it more or less scientific".

The most significant area of contention in NOS certainly concerns the realist versus the anti-realist (instrumental) views[92] of science. The realist view asserts that there is a reality independent of the scientist waiting to be uncovered and explained. The extreme realist believes that the entities (like electrons) that our successful theories postulate are copies of that reality. From a realists' perspective, students could certainly differentiate between three realms of reality[93] as: 1) that which is directly observable, 2) that which is observable by extending our senses (eg. microscope), and 3) indirect observation of the entities postulated by our theories (eg. model of the atom). While I don't believe we should pretend to advocate a realistic view which is "naive", i.e., that our scientific theories reflect an absolute truth, our students certainly could adopt some

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92 I am not advocating for any particular view here, rather the intention is to outline some characteristics of each view which could be discussed with high school students in some context.

93 Ron Harré, Varieties of Realism, Oxford, Blackwell, 1986.

kind of critical view as described by Hodson (1988)[94]. In this view, a critical realist, may believe that the entities that we postulate reflect the physical world, but, as we can never really be sure, our judgement on the exact nature of this world is suspended.

I would also suggest that older students can compare the realist's position with that of the instrumentalist. The instrumental position contends that whether something is real or not, is not at issue. Our theories and the entities they postulate are merely tools[95] that we use to explain the physical world. In this case, we do not adhere to one or another philosophical position but we advance (at least at an elementary level) the arguments of each position as each individual student builds their own NOS profile. Harré's realms of reality seems to be an appropriate starting point to address realism. Students readily adhere to the "seeing is believing" philosophy of the first two realms and they can be challenged to support this position in the realm of the micro-world.

Lederman (1998) outlined the characteristics of NOS that he believes are accessible to K - 12 students as: science is tentative, empirically-based, subjective, that science involves human imagination and creativity, and is socially and culturally embedded. Further, he argues for the distinction between observations and inferences, the lack of a single scientific method, and a consideration of the relationships which exist between scientific theories and laws. I believe that these characteristics are well supported by the history of NOS and that, along with the view that NOS itself is dynamic,

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94 Mathews calls this type of view modest realism.

95 or as Mach called them, "convenient fictions"

form a legitimate base for teaching NOS in school science at an appropriate level of sophistication. I also suggest that the controversies, in particular, the fundamental positions of the realist and instrumental views, are also accessible to the more mature student who can begin, finally, to form a more authentic view of science. However, we must realize that all of these views cannot be addressed in single lesson or without a context. Consequently, a period of time and a variety of contexts is necessary to develop these ideas. Additionally, we may only be able to deal with some of these ideas at an elementary level and re-visit them periodically as we increase the level of our expectations. This certainly means we need a NOS curriculum that is explicitly developed over a period of years. The research presented in this thesis is intended to advance a curriculum that deals in part with this development.

Another challenging question that remains concerns how we might develop such a curriculum and how we can begin to teach for a better understanding of NOS. In order to address this, we must first appraise what research tells us about the prior knowledge of our students, their teachers, and consider our experiences to date with instructional interventions to promote a better understanding of NOS.

Assessing the Nature of Science

Although many aspects of teaching the understanding of NOS had been proposed as early as the late part of the nineteenth century, a collective concern, and corresponding research, began to coalesce with the curriculum developments in the post-Sputnik era beginning in the 1950's. Mead and Metraux (1957) studied the opinions that students held on the role of the scientist. Although outdated, especially with respect to the views of young women[96], the research programs began to recognize that some form of measurement of understanding NOS needed to be developed. Wade (1999) lists almost thirty (30) NOS assessment instruments that were formed during a period of about forty years. Many of these instruments had serious shortcomings and are not of interest to this study. Some of these instruments, because of their significance in the development of test items and because of their popularity and relevance to this study are worthy mentioning. These tests include the Test on Understanding Science (Cooley & Klopfer, 1961), Science Process Inventory (Welch & Pella, 1967-68), Nature of Science Scale (Kimball, 1967-68), Nature of Science Test (Billeh & Hasan, 1975), Rubba's (1977) Nature of Scientific Knowledge Scale (NSKS), Conceptions of Scientific Theories Test (Cotham & Smith, 1981), and the Modified Nature of Scientific Knowledge Scale (Meichtry, 1992).

The format of most of the instruments was forced-choice, that is the respondents read a particular statement related to NOS and checked agree/disagree, a Likert-type scale, or selected an answer from a list of multiple-choice items. In order to provide a perspective in the history of assessing NOS two of the early instruments, Klopfer and Cooley's (1961) Test of Understanding Science (TOUS), and Rubba's (1977) Nature of Scientific Knowledge Scale (NSKS), are described briefly. They stand out for their popularity and the role that they played in the evolution of assessing NOS.

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96 One of the questions asked girls if they would consider marrying a scientist!

Test on Understanding Science (TOUS)

The Test on Understanding Science (TOUS) was developed by Cooley and Klopfer in 1961. The test consists of a four-alternative 60-item multiple choice test which contains three subscale scores:

(I) understanding about the scientific enterprise;
(II) the scientist;
(III) the methods and aims of science.

Subscale (III) is the scale mostly concerned with the aspects of the nature of science and includes questions on generalities about scientific method, on theories and models, and on the accumulation and falsification of scientific knowledge.

The TOUS was the most widely used assessment tool in "nature of science" research (Lederman et al.1998) and as the scope of the research in NOS began to broaden several criticisms of the TOUS became apparent. Initially, Hukens (1963) suggested that the complexity of some of the items could hinder the interpretation and meaning by the students. Later, Wheeler (1968) asserted that too many of the items embraced a negative viewpoint of science and Welch (1969) argued for stronger validity evidence for the TOUS calling for additional revisions to the TOUS. Further, Aikenhead (1973) reported that some TOUS items evoked a response of attitude and appreciation toward science and scientists resulting in a scientist's "good guy" image. In its time, the TOUS was considered to have made a significant contribution to understanding NOS and was used extensively in the early research. However, in hindsight, Wade et al. comments that "the TOUS exam appears inappropriate as a sole assessment instrument for the study of an individual's understanding of the nature of science" (p. 806).

Nature of Scientific Knowledge Scale (NSKS)

The Nature of Scientific Knowledge Scale (NSKS) test developed by Peter Rubba in 1977 consists of 48 Likert style questions. Initially, Rubba developed a model of the nature of scientific knowledge following the work on science literacy by Victor Showalter (1974). Rubba coalesced Showalter nature of scientific knowledge into six factors which included Amoral, Creative, Developmental, Parsimonious, Testable, and Unified characteristics of scientific knowledge. Eight individual questions, four which addressed positive statements and four which addressed negative statements, were written for each factor.

The most obvious problem with the NSKS surrounds the fact that many of the positive and negative statements in the test were merely mirror opposites of each other. For example, on theories and laws the questions read:

Scientific laws, theories, and concepts do not express creativity,

and Scientific laws, theories, and concepts express creativity.

Wade et al. (1999) claimed that this would inflate reliability estimates as students could consult the answer they gave to the partner question. An additional concern might include misreading the statements as identical statements, and while giving the same answer they would be graded as opposites. Cotham (1979) also criticized the test for its lack of sensitivity to alternative views. Indeed, Peter Rubba, one of the developers of NSKS stated that he did not feel that the NSKS was a very good measure of the nature of science (Rubba, personal communication) and directed me towards Aikenhead's VOST. In spite of such criticism, the NSKS was also widely used by researchers.

All of the early NOS assessment instruments contained a fairly large number of items (in some cases over 100). As a result, the evaluation of these instruments was based on economy. A large pool of questions with responses on a agree/disagree or a Likert scale were easy to grade and even easier to analyze. Usually, the evaluation of a students' views of NOS were labelled adequate or inadequate based on a cumulative score that provided little insight into the details of students' views on NOS. Moreover, assessing the meaningfulness and importance of any gains in understanding NOS, as in this thesis, would be problematic.

Cotham and Smith (1981) also pointed out that each instrument assumed that its interpretation of NOS was the "enlightened one". In some cases[97], an individual with a Popperian outlook would check agree while someone else with a Kuhnian view would disagree. They state that,

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[97] Cotham and Smith cite an example from Lucas (1975). Lucas evaluates the NOS statement that "Science is a series of successively closer approximations to the truth" and concludes that some with a Kuhnian point of view would disagree while someone with a Popperian outlook would agree.

> "the significant question is not whether a person's view on the nature of science conforms to a particular espoused viewpoint, but rather, what are the limits of the person's understandings and how do their understandings affect their choices and behaviours" (p. 814).

They recommended in the analysis of these types of statements that a non-judgmental interpretation be used. This of course, severely limits the use of a cumulative score to determine adequate or inadequate views of NOS.

The TOUS and the NSKS provided a beginning for those interested in assessing understandings of the nature of science and both were used extensively. Later, studies improved on this methodology by incorporating open-ended responses and interview techniques. These strategies permitted the researcher to probe students' responses and to ensure that their interpretations of certain statements were accurate. Two of these instruments were Aikenhead's (1987), Views on Science - Technology - Society (VOST) and Lederman and O'Malley's Views of the Nature of Science questionnaire (VNOS, 1990).

Views on Science - Technology - Society

Aikenhead (1987) believed that the current slate of assessing NOS instruments, which used a forced response in the form of agree/disagree or a Likert scale all had an implicit assumption. Both the researcher and the student are believed to perceive the same meaning in reading the test item. Munby (1983) called this "the doctrine of immaculate perception"(p. 207). In other words, a test item that may seem to be objective to the researcher may be quite subjective to the respondent.

In his research, Aikenhead reported several severe problems with these types of tests. He found that for 85% of all of the student positions that the students wrote similar arguments but selected different Likert-type answers. As a consequence, Aikenhead developed the Views on Science - Teaching - Technology - Society (VOSTS) test which required students to use an argumentative response to a statement about a STS[98] subject (of which one category was the nature of science). In this way, the researchers was not checking for right or wrong answers but they had to assess how students defined and defended their positions on various aspects of STS issues. This format enabled the researcher to detail the reasons that students gave to justify their opinions. Additionally, students were not forced into selecting an answer and could respond "I do not understand" or in some cases, "I don't know enough about this subject to make a choice".

In 1984, Aikenhead used the VOSTS test in a large Canadian survey of 10 800 students. Forty-six test items had been identified, however, each student responded to only one open ended item. In this way, the researchers had approximately 230 responses for each test item. A sample of 30%, chosen randomly and stratified for regional disparity, resulted in a data base of about 70 responses for each item. Finally, students' responses were summarized and grouped into common categories.

The analysis of the students' written responses did not necessarily eliminate all errors of interpretation but it did help make the interpretation of the researcher more

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98 Science - Technology - Society

transparent and consistent. Students' written work, especially younger students, is not unambiguous and researchers could still fall into the doctrine of immaculate perception interpretation. Additional clarification was necessary to determine where the respondent's ideas came from, what exactly did they mean by terms such as the scientific method, how strong did they hold their ideas, and how resistant were these ideas to change? Using the open ended response format researchers could compare their evaluations increasing the level of confidence in the assessment of students' interpretations. Aikenhead further recommended that additional probing of student beliefs could be enhanced with other techniques such as interviews.

Views of the Nature of Science questionnaire (VNOS)

Lederman and O'Malley (1990) developed the VNOS as a response to their perceived deficiency of previous tests to provide an adequate insight into NOS. The VNOS was a seven item open-ended questionnaire which was used with follow up interviews to probe and clarify student responses to understanding NOS. The interviews also permitted the researcher to assess the students' justification for their views and to identify the source of these views. The questionnaire was open-ended to allow students to express their own views and the reasons that underlie these views. To avoid the misinterpretation follow up interviews were used to substantiate and establish the validity of the test items. As a result of this method, Lederman and O'Malley were able to formulate in-depth profiles of students views in NOS across a broad range.

The questions on the VNOS-A included:

1. After scientists have developed a theory (e.g., atomic theory), does the theory ever change? If you believe that theories change, explain why we bother to learn about theories. Defend your answer with examples.

2. What does an atom look like? How do scientists know that an atom looks like what you have described or drawn?

3. Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.

4. How are science and art similar? How are they different?

5. Scientists perform scientific experiments/investigations when trying to solve problems. Do scientists use their creativity and imagination during these experiments/investigations?

6. Is there a difference between scientific knowledge and opinion? Give an example to illustrate your answer.

7. Some astrophysicists believe that the universe is expanding while others believe that it is shrinking; still others believe that the universe is in a static state without any expansion or shrinkage. How are these different conclusions possible if all of these scientists are looking at the same experiments and data?

The early instruments, such as the TOUS and NSKS, used to assess NOS may reveal something about NOS but they are limited in providing any kind of detailed understanding about individual beliefs and the development of these beliefs. For adolescents, these beliefs are often in transition and they often hold conflicting views about different aspects of NOS. The intention of this study was to assess the change in students' understanding of NOS through an intervention that included the historical development of a conceptual model. An in-depth profile of each students' understanding of NOS required this researcher to value students views and eliminate the necessity of a forced choice item assessment. Ebenezer and Erickson (1996) reported that interview data "often provide rich insights in the sources of students' conceptions". In this light, an open ended format was desired that could probe student responses through interviews. Consequently, the VNOS was selected as the most appropriate assessment instrument for this thesis.

Research of Students' Views of NOS

While the assessment instruments for NOS have demonstrated many weaknesses one of the most surprising results from the use of the instruments is their consistent agreement concerning students' understanding of NOS. Early studies using instruments like the TOUS and the NKSK, outlined students' lack of understanding of the nature of science (Aikenhead, 1973, Mackay, 1971, Rubba & Anderson, 1978). Mackay in a large study of over 1200 grade 7 - 10 students summarized that the common deficiencies of students included a lack of appreciation of the relationship between models, theories and absolute truth, hypotheses, laws, and theories, the function of the scientific model, the role of creativity in science, and the dynamic nature of science. Rubba (1977) in studies associated with the development of the NSKS reported 30% of the students taking science at a large midwestern high school believed that scientific research uncovers absolute truth. He also indicated that "students believed almost invariably that scientific theories, with constant testing and confirmation, eventually mature into laws" (Rubba, Horner & Smith, 1981, p 221).

In a large Canadian study, using an open-ended instrument, Aikenhead (1987) found that students' answers reflected some ideals of authentic science such as the nature of classification schemes, the tentativeness of models and theories, and the social dimensions of knowledge. However, students emerged less informed on the nature of scientific models, outside influences, motivations for generating knowledge, and on scientific method. Aikenhead also reported that students were not confident with discussing these issues, suggesting that their instruction in the understanding of the nature of science is obscured and is assumed implicit with the instruction of the knowledge outcomes.

Ryan and Aikenhead (1992) extended the 1987 study using the VOSTS instrument and reported that the majority of students (64%) expressed a simplistic hierarchical relationship in which hypotheses become theories and theories become laws, depending on the amount of "proof behind the idea." In terms of the tentativeness of science, they reported that students fall equally into three categories, the constructivists, the falsificationists, and the excessive rationalists. The constructivists see science as continually changing, especially with the discovery of new evidence or conceptual schemes. The falsificationists consider that science progresses by disproving scientific knowledge and the excessive rationalists believed that scientific facts were unchangeably true.

Lederman and O'Malley (1990) also suggested that, on the whole, students did not adhere to either an absolutist or tentative view of science. However, students' responses did become more clear when they were given a chance to explain themselves in interviews. In these interviews, students often failed to justify their beliefs leading

Lederman and O'Malley to conclude that "The inability of most students to identify the sources of their beliefs appears to indicate that an understanding of the nature of science is taught and learned implicitly" (p. 235). Lederman (1998) further suggests, "the longevity of this educational objective has been surpassed only by the longevity of students' inability to articulate the meaning of the phrase 'nature of science" (p 1).

More recently, Griffiths and Barry (1993) investigated the views of 32 subjects between the ages of 17 and 20 for their views on NOS. All of the students were interviewed using a set of standard questions surrounding change in science, and the nature of scientific facts, theories, and laws. Most of the questions were direct attempts to find out what students thought about a particular aspect of NOS. Typical questions were, "what is science?, how does science change?, what is meant by a fact in science?, what is meant by a theory in science? and, are facts and theories open to change?" They found that, in general, students' responses referred to school science rather than science as practised by scientists. Students saw science as improving upon itself in light of new questions and they maintained a hierarchical relationship between facts, laws, and theories in science. However, even though students seemed to attribute greater status to laws as proven theories many still agreed, on some level, that laws could change.

The Griffiths and Barry study was extended to schools in the United States and Australia. A total of 96 students (32 in each country) were interviewed using the same format as described above (Griffiths & Barman, 1995). Several interesting differences were cited between the countries, in particular with respect to methodology. A much more mechanistic view with a strict adherence to the scientific method was reflected by the American students. In the study 60% of the American students responded that science does not change compared to 15% of the Australians and zero percent of the Canadians. For students who believed that theories could change 40% of the Canadian students felt that new ideas could lead to the change, while only 15% of the Australians and zero percent of the Americans advanced this view.

Griffiths and Barry also identified two trends that they see as progressions in a learner's reflection on the nature of scientific theories and laws. The first is the belief that theories advance from an idea, to an educated guess and finally to a theory (hypothesis). The second trend concerns the belief in the progression from a theory to a fact to a law also referred to by McComas as the number one myth in the understanding the nature of science. I consider this view to be a reflection of the way learners really do think about theories in science. Commonly, they conflate the notion of a theory to a simplistic view without understanding that a theory is a much more complex thing and covers a spectrum of ideas. This spectrum ranges range from speculative hypotheses with little or no supporting evidence to robust scientific theories that possess considerable and diverse support.

Saunders (2001) employed a more general approach to investigate students' understanding of NOS. He simply asked the students to answer the question, "What is Science?". He found that students' notions of science overwhelmingly focused on subject matter. The responses usually began with "science is the study of .." and finished with a topical reference such as cells, the human body, everything. Surprisingly, for the last ten years I have asked my students the same question on the first day of school with similar results. However, I do not concur with Saunders that this information in any way informs us of students' understanding of the various aspects of NOS such as models, laws, theories, theory choice and so on. Nor would I dare, as Saunders does, speculate from their answers, how students develop their understanding of NOS. Instead, my classroom experience mostly reflected what students studied in their previous year and they thought little about NOS.

To summarize, current research strongly indicates that students possess inadequate knowledge of the nature of science, moreover, the inability of students to identify sources or influences of their beliefs, highlights a paradoxical situation. Regrettably, while clearly stated as a valued goal, the understanding of the NOS is often assumed to be absorbed within the content delivery of the discipline. At the same time research in education ostensibly demonstrates that the achievement of these goals are suspect regardless of the methodology. Lederman (1992) reports on a broad range of studies over 30 years and asserts

> "The overwhelming conclusion that students did not possess adequate conceptions of the nature of science or scientific reasoning is particularly significant when one realizes that a wide variety of assessment instruments were used throughout the aforementioned research". (p 335)

The poor performance of students' understanding of NOS issues began to raise questions about their teachers' understanding of NOS, subsequently, research began to investigate the teachers' understanding of NOS.

Teachers' Views of NOS

Many of the early investigations of teachers' knowledge of the nature of science were not flattering suggesting that teachers do not understand science as well as their students (Miller, 1963, Schmidt, 1967, Lederman and Druger, 1985). Additional studies (Hodson, 1993, Lederman, 1995) suggested that even when teachers had adequate conceptions of the nature of science these conceptions did not necessarily influence their instruction in the classroom.

More recently, studies on teacher's conceptions of NOS have started to gather more in-depth information. Gallagher (1991) conducted a study of 27 secondary school teachers to determine what viewpoints about science were being presented to students and what did teachers understand about the nature of science. Most of the teachers in his study had majors or minors in their subject area and had at least ten years of teaching experience. After observing more than 1000 classes and conducting numerous formal interviews Gallagher noted that

> "The views of the nature of science held by 25 of the teachers in our study are unsettling. Our observations of their classes showed that all teachers placed most of their emphasis on the body on knowledge of science"[99]

He found that most of the teachers emphasized the content knowledge of science with a particular emphasis on vocabulary. In their classes, the teachers started the year stressing the objective nature of science through the steps of the scientific method. In spite of this

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[99] Gallagher, p 124, Prospective and practising secondary school science teachers' knowledge and beliefs about the philosophy of science.

naive representation of science, the teachers rarely referred to methodology or the development of knowledge in the course of the year as the teachers focused primarily on content knowledge with infrequent laboratory exercises. Gallagher concluded that the teachers taught in this way because of their university preparation which stressed rapid coverage of the content of science that included little recognition of the origins or applications of science and that they lacked experience in the history, philosophy, or sociology of science to enable an integrated understanding of scientific knowledge.

Gallagher's assertion that teachers did not receive an adequate understanding of NOS through their university experience is supported by the research of Aguirre, Haggerty, and Lindor (1990). In their study of 74 student teachers who had just completed a major in pure or applied science, they found that 40% held naive views in NOS. Aguirre et al. also expressed the belief that there might be some connections between the views held by the pre-service teachers about NOS and the views they hold about the teaching practice. Almost 50% of these pre-service teachers considered teaching to be a matter of knowledge transfer from the teacher and textbooks to the student. A further 50% (however, not always the same individuals) expressed a view of learning as just an intake of knowledge.

How a teachers' conceptions in NOS influence their teaching remains open to debate. Lederman (1992) reminds us that

> "science educators concerns must extend well beyond teachers' understanding of the nature of science, as the translation of these understandings into classroom practice is mediated by a set of complex variables" (p. 351).

We might point to limited professional development, class size, a lack of preparation time and resources, and a concern for standard assessments, as just a few of the influences that determine the nature of the teaching practice and strategies employed in the classroom. Teachers' views of NOS, like their students, may also be only partially developed. Koulaidis and Ogborn (1989) advise us that teachers hold "eclectic or mixed" views of NOS, and in Zimmerman and Gilbert's (1998) case study, we are introduced to a teacher who holds mixed views but acts on only one of these views in practice. The researchers attribute these mixed views to the varying influence of historical, educational, and cultural experiences of the teacher and explain the different views of their subject Sergio.

> "Under the influence of his readings of the history of science, Sergio is inclined to see science within a contextualist model, while, when reflecting on his school based knowledge and on his wish to deny pseudoscience, his view is inductivist. His determination to show to his students the irrationality of knowledge derived from religion compels him to present science in his classroom within an inductivist model of science, a model which is consistent with his own school experiences. Thus, he keeps his contextualist view of science outside of the classroom" (p. 215).

Brickhouse (1990) used several case studies to investigate teachers' understanding of NOS and how their classroom practice reflected this understanding. Three teachers were purposely selected for their diverse perspectives on the nature of science. Although small in scale, the study was quite comprehensive. The teachers were questioned in a series of interviews four hours long and their classrooms were observed for at least 35 hours. Additional information was obtained through the collection and analysis of the textbooks that each teacher used, tests, worksheets, and laboratory activities. A case study was written for each teacher and was reviewed by the teacher for accuracy.

The teachers' views on the nature of scientific theories, the nature of scientific processes, and the progression and change of scientific knowledge were investigated. At one end of the scale, one teacher demonstrated a Kuhnian point of view which considers theories to be tools useful for problem solving. Teacher #1 believed that science progresses not only with new observations but also through new interpretations of these observations. She also maintained that students sometimes learned through conceptual leaps in a manner analogous to Kuhn's scientific revolutions[100]. In her classroom she emphasized the interplay between observation and theory and she explained to her students that theories were strengthened by prediction and observation. The nature of scientific theories was a persistant theme in this teacher's classroom and her students were persuaded to predict the outcome of demonstrations and experiments and they used theories to explain their observations and to ponder new problems.

Teacher #2 viewed theories as truths that were uncovered through experimentation and that science progressed by a gradual accumulation of knowledge. This teacher wanted his students to know the theories by memorization and his activities and assessment of his students were dependent on the presence or absence of the right or wrong answer. Brickhouse points out that while this teacher taught the products and

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100 We might also consider this to be analogous to Piaget's assimilation experience in learning or, a form of Posner's view of conceptual change which relies on both Kuhn and Piaget analogies.

processes of science, he taught them separately. He either taught the facts and theories without examining how these facts and theories were formulated or he taught scientific processes leaving out the role of the theory in understanding and explaining these processes. Teacher #2 adhered to a strict, procedural scientific method which was reflected in his classroom practice. His science activities were based on following the right directions (as in a recipe) in order to arrive at the right answers (typically a word or a number which was entered into a formatted worksheet). In this class, students' questions were usually only of a procedural nature and in the case of error, students were required to repeat the routine until they got the right answer.

Teacher #3 also viewed scientific progress as an accumulation of knowledge rather than by the revision of theory. Brickhouse describes how this teacher's idea of accumulated knowledge was reproduced in his teaching. For example, he described the development of the atomic model as one model building upon the previous model and his questioning techniques were congruent with a gradual acquisition of knowledge. This strategy was consistent with Piagetian process of assimilation where new information is interpreted using a current set of beliefs. That is, the learner's conceptual change is only the result of additional knowledge as opposed to changes in their conceptual structures.

Even though teacher #3 espoused a step by step scientific method his teaching practices sometimes challenged his belief that science progressed linearly. He used historical vignettes, such as the story of the alpha helix, that revealed serendipitous moments in discovery. Brickhouse offers two explanations for this variation between belief and practice. The textbook used by the teacher was viewed as an authority by the teacher and the textbook described a scientific method common to all scientists. Additionally, the teacher believed that his students needed the structure of a scientific method to guide them in their activities. Since Yager reports that 90% of the teachers use the textbook 90% of the time it is not surprising that the textbook wields considerable influence in the planning and practice of teaching science.

Brickhouse concluded by identifying three aspects of NOS that she believes are important for teachers to understand. First, she advocates a Kuhnian view that theories in science are socially-constructed and they serve as devices for organizing and interpreting knowledge and solving problems. From this position, the evaluation of theories is based on a set of agreed upon criteria such as empirical accuracy, values, scope and this evaluation takes place in a social context[101]. In this perspective Brickhouse asserts that the goal of science education is to bridge the gap between the learner's experience and the culture of science. By favouring a Kuhnian perspective Brickhouse highlights the position advanced by Lucas' criticism of NOS assessment tools, that is, each instrument assumed that its' interpretation of NOS was the "enlightened one".. It is my belief that the teachers in this study do not necessarily need to move towards a Kuhnian perspective to become better teachers of science, but rather they need to better and more clearly understand this perspective and at least defend their own views in a more than naive fashion.

Secondly, Brickhouse suggests that teachers should understand the relationship

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101 Kuhn details the evaluation of scientific theories in his essay Objectivity, Value Judgement, and Theory Choice in The Essential Tension, p 320 - 329.

between theory and observation. Brickhouse draws a comparison between the theoretical commitments of the scientist and the interpretation of observation in the classroom by the learner. That is, all observations of the scientist are theory-laden and knowing what to look for guides the scientists as much as it should guide the student. Additionally, she maintains that students should be aware of the relationship between theory and evidence, they should be critical of their own ideas, and they should be encouraged to create alternative theories. Finally, Brickhouse maintains that the nature of scientific process is best represented as a revisionary process rather than a cumulative process. In this way, learning in science involves building on and changing prior conceptions, a view more closely aligned with constructivism.

Although this study was small in numbers, I believe that Brickhouse has identified some very critical issues concerning teachers with respect to improving instruction in NOS. Brickhouse suggests that the teachers' philosophy of science had been fashioned through their own experiences but that those experiences were often based on constraint and tradition. As mentioned previously, these constraints include such problems as academic preparation, time management problems as well as a lack of professional opportunities. In terms of NOS outcomes, curriculum constraints must also be considered. On one end of the scale, as seen in Ontario, the NOS outcomes are non-existent and, in jurisdictions where NOS outcomes are found, the integration and context of these outcomes has been left to the designs of teacher. The teacher also needs to be compelled to address the different aspects of NOS in context such that they examine and develop their own views. A reasonable way to accomplish this is to explicitly integrate the NOS outcomes with a historical approach in the designed curriculum. This would establish a framework which would required the teacher to reflect on the different aspects of NOS explicitly while they are "teaching science".

Shapiro (1996) uses a form of reflective inquiry to promote explicit attention to NOS outcomes with prospective elementary teachers. The aspects of NOS the students were asked to discuss and reflect on during independent investigations included creativity and imagination in science, subjectivity, and scientific method. Shapiro reports that such a framework focused students attention to NOS questions they would not normally be aware of if the outcomes had been left to chance. This does not just pertain to the inexperienced teachers. In another study, Schwartz, Lederman, and Thompson (2001) highlight a teacher who states, while reflecting on NOS feedback from his colleague, "it forced me to think one more time about how to explicitly connect what I was doing in the classroom to an understanding of science" (p. 21).

Intervention studies to Influence Teacher Understanding of NOS

The growing body of research which indicated that students and their teachers lacked an informed understanding of NOS naturally led to interventions which were intended to improve the teacher's understandings of NOS. Abd-El-Khalick (1999), and later Abd-El Khalick and Lederman (2000), provide an extensive review of 17 studies which they separate according to whether the intervention is implicit or explicit. These studies included pre-service and in-service teachers as well as science majors and non-majors who may be candidates for the profession. An implicit approach attempts to foster an understanding of NOS through process skill instruction, science content coursework, and “doing science”. Abd-El-Khalick and Lederman characterize an explicit approach as one which uses elements from history and philosophy of science and/or makes reference to, and reflects on, specific aspects of NOS.

The implicit studies employed a variety of intervention treatments including curriculum projects (Trembath, 1972), hands-on inquiry-based activities (Barufaldi, Bethel, & Lamb, 1977, Riley, 1979), structured investigations which emphasized verification labs versus un-structured labs which promoted discovery (Spears & Zollman, 1977, Haukoos & Penick, 1983, Haukoos & Penick, 1985), and diversified lecture activities/discussion/readings (Scharmann, 1990, Scharmann & Harris, 1992). In terms of their relative success, four of the studies (Sears & Zollman, 1977; Haukoos & Penick, 1985; Riley, 1979; and Scharmann & Harris, 1992) reported no significant gains in understanding of NOS as measured by NOS assessment instruments (TOUS, NOSS, SPI) and one study (Scharmann, 1990) suffered from lack of data. Three studies (Barufaldi, Bethel, & Lamb, 1977; Spears & Zollman, 1977; Haukoos & Penick, 1983) reported small gains but the Haukoos & Penick study could not be replicated in 1985 and the Spears and Zollman study only showed a small gain of 2.5% on one component of the SPI test. One study (Trembath, 1972) reported a 20.5% gain in post-test results compared to a control group but it should be noted that this score increase from 7.0 to 10.7 on an 18 point scale.

Abd-El-Khalick and Lederman also outlined nine studies they consider to promote an explicit treatment of NOS where participants were always asked to reflect on various aspects of NOS in some formal, organized activity. Two categories of studies emerged from this review. One set of six studies utilized in some part the history and philosophy of science by integrating narratives, articles and books with science content (Carey & Stauss, 1968; Carey & Stauss, 1970; Jones, 1969; Lavach, 1969, Ogunniyi, 1983, Akinedehin, 1988). The second group of studies addressed the characteristics of NOS explicitly in lectures, guided discovery activities, and laboratory sessions (Olstad, 1969; Billeh & Hasan, 1975; Shapiro, 1996). Seven of the studies reported significant gains on standardized NOS instruments ranging from 3% to 11%. One study (Akindehin, 1988) lacked comparative data but post-treatment scores were the highest achieved among all groups and one study (Shapiro, 1996) used qualitative methods to follow the development of NOS ideas in one participant.

Abd-El-Khalick and Lederman concluded that "an explicit approach was generally effective in fostering appropriate conceptions of NOS views among prospective and practicing science teachers" and that "approaches that utilize elements from history and philosophy of science and/or direct instruction on NOS are more effective in achieving that end than approaches that utilize science process-skills instruction or non-reflective inquiry-based activities" (p. 692). However, it should be noted that the researchers highlight three features which they feel also characterized the aforementioned studies. First, the statistically significant gains were generally very small, secondly, the post-test scores were typically low, indicating that limited understanding of NOS had been achieved. Finally, many of the reviewed studies initiated interventions across relatively short time frames.

Intervention Studies to Influence Student Understanding of NOS

One of the earliest interventions studies to measure and improve students' understanding of NOS was administered by Klopfer and Cooley (1963), the developers of the TOUS assessment tool. These researchers were motivated by earlier research, such as the Mead and Metraux (1957) study, that found students' understanding of NOS to "quite inadequate" and "particularly disturbing" since many students' views represented "gross distortions" of a realistic understanding of science. Klopfer and Cooley recognized that there was a lack of instructional strategies and resources to foster the understanding of NOS so Klopfer developed a series of History of Science Case Studies (HOSC) to address several important aspects of NOS. The case studies were intended to be used in existing biology, chemistry, and physics high school science courses and contained historical narratives, quotes from original sources, pertinent student experiments, marginal notes and questions. Additional teacher supplies including supplementary books, articles, and supplies were also prepared.

An experimental design was established to address the questions: "Do students who study under the HOSC Instruction Method as a part of their regular science class work achieve significantly greater gains in their understanding of science and scientists than students who do not, and, do students who study under the HOSC Instruction Method as a part of their regular science class work show as much achievement in the usual content of the science course as students who do not? Students were divided into experimental and control groups and wrote pre and post tests to assess their understanding of NOS (using the TOUS) as well as standardized tests to assess their achievement in the normal content of the course.

The HOSC Instructional project commenced in April 1960 at Harvard University. A total of 108 teachers and their students (n = 2808) were recruited and pre-tests were administered in the September and October, at the beginning of the school year. The teachers selected two[102] historical case studies to incorporate into their instruction and they maintained control of scheduling and sequence of the units. The typical time to complete a unit was ten or eleven class periods and in March/April students wrote the TOUS and achievement tests.

In this study, Klopfer and Cooley have carefully measured and controlled three effects. Effect A is the instruction method itself, HOSC vs the control group; effect B in the teacher's initial understanding of NOS. At the beginning of the year the teachers wrote the TOUS and in the analysis they were divided into two groups, one rated high understanding of NOS and the other low understanding of NOS. A third effect, effect C was the type of science course, either chemistry, physics, or biology. In their findings, Klopfer and Cooley reported that both the experimental group and the control group increased their understanding of NOS as measured by the TOUS. However, the gain of experimental group was considerably greater (increase of 5.09 vs 2.10). The researchers also reported the interactions between the three effects. They found that the gains in

[102] a total of eight case studies had been produced, three in biology including the Sexuality of Plants, Frogs and Batteries and the Cells of Life; two in chemistry, The Discovery of Bromine and the Chemistry of Fixed Air; and three in physics, Fraunhofer Lines, The Speed of Light, and Air Pressure.

student understanding of NOS did not depend on the teacher's initial understanding of NOS. Students of teachers rated low gained equally with students of teachers rated high on the NOS scale. Additionally, in a cross factorial analysis of effects A and C[103] they found that there were no significant differences in achievement in the usual content in the physics and chemistry classes and a small difference[104] in the achievement of the biology content in favour of the control group.

As a result of the large sampling, careful controls and cross-factorial analysis the researchers reported their findings with confidence. They also suggested that the small decrease in achievement in biology is more than adequately offset by the students corresponding increase in their understanding of NOS. Particularly interesting is the result that the teacher's initial understanding of NOS did not play a role in the students' gain in understanding NOS. I have previously indicated references (Hodson, 1993; Lederman, 1995) that suggested that even teachers who have an understanding of NOS do not necessarily reflect that understanding in their instruction. However we might consider another possible reason for this outcome. Teachers rated low improved their understanding of NOS as they taught. It is not unusual to hear an experienced teacher say that "I learned all of my physics in the first year I taught it". This potential for improvement in teacher's understanding of NOS is tremendous given that so few are reached in their teacher preparation. However, in order to move teachers in this direction

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[103] an additional control for aptitude was also included.

[104] a difference that amounts to the approximate equivalent of two questions

curricular outcomes for NOS must be explicitly stated in the curriculum In other words, the curriculum must enable the possibility of the teacher consciously reflecting on NOS in order for any chance of this type of independent learning to occour.

Another Harvard program based on the history of science was Project Physics. Gerald Holton, F. James Rutherford, and Fletcher Wastson (1970) developed a humanistic approach to teaching physics by blending good physics with good history of science. Although not specifically designed as an intervention to improve students' understanding of NOS is seemed natural to many educators to compare these students with students in other physics programs (most notably at the time PSSC physics) . Several studies on the effectiveness of the Project Physics course yielded mixed results[105]. Welch (1973) reported on a number of significant differences between the Project Physics course and other physics courses including students' increased satisfaction with the historical approach. However, no significant differences were reported on their understanding of NOS as measured by the TOUS.

In spite of the apparent success of the programs and resources in the history of science coming out of Harvard (HOSC and Project Physics) few research studies took an interest in continuing investigations into the use of history and philosophy of science in improving students' conceptions of NOS. One reason may be that interest waned in the Harvard projects once government funding for their summer institutes was withdrawn and teachers, unprepared in the history and philosophy of science, were once again left to

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105 For a summary of the studies and their results see Ahlgren and Walberg 1973 or Welch 1973.

their own designs. Eventually, the Project Physics text went out of print. Another reason may have been educational researchers became engaged in the growing interest in inquiry in the curriculum reforms of the 1960's. As researchers began to highlight some of the problems of inquiry and students' understanding of NOS some additional intervention studies appeared.

Solomon, Duveen, Scot, and McCarthy (1992) also utilized historical units in an instructional study. Their research was in response to the National Curriculum for England and Wales which included a section on the history of science. The stated objective relevant to NOS was:

> "Pupils should develop their knowledge and understanding of the ways in which scientific ideas change through time and how the nature of these ideas and the uses to which they are put are affected by the social, moral, spiritual and cultural contexts in which they are developed" (p. 68).

The intended outcomes included the history of science and Solomon et al. commented that "the requirement to teach history of science found the British school system largely unprepared" with no classroom resources and little understanding of what the teaching of the history of science would accomplish. These concerns guided their study to observe how learning science through historical perspectives might influence students' understanding of NOS, as well as their attainment of scientific concepts. In their study, Solomon et al. included teachers as co-researchers in five classrooms across three different schools. The researchers often worked with the teachers to "recognize and bring about good practice", however, they claimed that once the lessons were over they interviewed rather than helped the students. The teaching resources consisted of 13 modules subsequently published as *Exploring the Nature of Science* (Solomon, 1991b). A selection of historical vignettes were chosen to comply with the national curriculum objectives and the modules included practical laboratory and DART[106] activities. For example, the *Mountains on the Moon* unit follows the story of the development of the telescope from the early use of lenses to Galileo's discovery of the lengthening shadows of craters on the moon. Subsequently, ancient beliefs of heavenly perfection were compared to the new "imperfect" moon. In the associated DART activities groups of students made posters of their episode and modeling wax and a soccer ball were used to form a "moon" with craters. The "moon" was illuminated with a projector beam and students completed measurements to show that the length of the shadow and the angle of illumination were related to the height of the "craters" on the model moon.

Similar to Klopfer and Cooley (1963) and unlike other studies, the researchers were careful not to rely on a single module to address the teaching of NOS. The teachers who participated in the study chose six of the thirteen units to teach with the intention being to build upon NOS ideas at regular intervals during the years.

The researchers developed a four item questionnaire which was administered as a pre and post test to 94 students. Additionally, students were interviewed in focus groups. In the analysis of the data, the researchers reported that the students views on experimentation moved from seeing the purpose of experiments as a means of discovery

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[106] DART stands for Directed Activity Related to Text. Sample activities might include making posters, sequencing of statements, or role playing. The idea is for students to re-examine the text they are reading for additional information. For more detail see Davies and Green (1984).

toward the view that experiments could be used for trying out explanations. Secondly, more students, after instruction, responded that scientists know what they expect to happen in an experiment. Thirdly, fewer students responded that theories were facts and they began to see theories as ideas and explanations. Finally, the researchers concluded that their units of instruction for teaching the history of science integrated with the regular school curriculum made a valuable contribution to the students' understanding of certain aspects of NOS. They especially point out that students' ideas began to move away from the view of scientific experiments as "serendipitous empiricism" to an appreciation of the relationship between theory and experimentation in science. Although all of the participating teachers expressed the view that their students had learned some scientific concepts better through studying them in a historical perspective, the researchers were careful to note that this could be the result of an "innovation enthusiasm" and the extra classroom help that was provided to the students. Solomon et al. also disclosed an uncertainty about how the modules affected the understanding of the history of scientific ideas and the development of a more mature insight to the social relevance of science. However, they did claim that using historical materials seemed to produce more "durable" learning and that "helping the pupils focus on the reasons for accepting one theory rather than another was more effective than just teaching accepted theory" (p. n-2).

In another British study, Irwin (2000) conducted an action research investigation with two groups of year 9 students (age 14 years). The design of the instruction, the instruction itself, and the analysis were carried out by this one researcher. Two classes, of 25 students each, were taught using a historical theme (HTG group) and using a traditional "final form" approach (FFG group). Each group was taught eight lessons on the topic "Atoms and the Periodic Table" with the HTG group receiving an emphasis on theory development in a historical context in their first four lessons. In this intervention, the first three classes focused on the idea of an atom as an indivisible particle. Irwin used the article "Empirical Foundations of Atomism in Ancient Greek Philosophy" (Sakkopoulos & Vitoratos, 1996) to describe the indirect evidence used to support the existence of an atom. Students were challenged by thought experiments such as the problem of slicing a cone horizontally. They were asked the question, "Is the upper surface the same size as the lower surface"?, and were led to the conclusion that if the lower surface were not at least one atom larger, then the cone would be a cylinder. The following classes examined Dalton's model of the atom and some of the "mistakes" that he made, such as his contention that water was a combination of one atom of hydrogen and one atom of oxygen (HO). Finally, students considered the early attempts at finding a pattern for the elements and the development of the periodic table.

The FFG group were taught in a logical sequence in a traditional manner with an emphasis on modern atomic theory. Students were typically given definitions and the statements of the final products of science and they had no opportunity for philosophical discussions. The final four lessons (classes 5 - 8) for each group were the same and consisted of the conventional treatment on periodicity and the groups of the Periodic Table.

Both groups of students were given a pre and post test to examine their content knowledge. Irwin reports no significant differences in the content knowledge of the students after instruction. Additionally, each student wrote a post instruction questionnaire which was developed by the researcher. The questions addressed some aspects of NOS such as "Were atoms discovered or did somebody imagine them?" However, other questions seemed a bit more tenuous. For example, "Which would impress you most - a theory that explained things we already know about or a theory that predicts things yet to be discovered?" and "Which of these is taking the bigger risk?" Most students, in both groups (HTG n = 15, FFG, n = 18), selected a predictive theory. What this reveals about students understanding of theories, or theory choice, is not clear at all. It is difficult to imagine how the complex nature of models, laws, and theories can be addressed in so few classes and why students might choose a predictive theory over an theory that explains things. Irwin appears to be leading the students to adhere to a Popperian view of the "riskiness" and refutation of theories as if he were teaching a "final form" philosophy of science.

Another significant weakness of this study was the role of the teacher/researcher, especially in the follow up interviews. Interviews are commonly used to probe students' understanding and to give students a chance to clarify their views (Lederman & O'Malley, 1990). However, instead of one on one interviews to enable students views to be heard, Irwin organized a focus group of seven students (4 HTG and 3 FFG). The focus group was pre-selected by Irwin as a result of interesting comments, either oral or written that the students had made during the study. During the interview, Irwin seriously jeopardizes the study by playing the role of a teacher rather than a researcher. He admits that, "the transcript of the tape could be viewed as a series of leading questions in which I invited the answers I was looking for, or in some cases provided those answers myself" (p 13).

In spite of the serious limitations of time spent on the historical approach (parts of 4 lessons) and the obvious problems of the interview of the focus group, Irwin does report some interesting observations. In response to the question, "Were atoms discovered or did somebody imagine them?", all of the students in the FFG (n = 24) answered that atoms were discovered. Eight members of the HTG (n = 18) group responded that atoms were imagined. Irwin correctly points out that most pupils adopt a "realist" point of view of the atom, that is, they clearly accept that atoms exist in nature. Although many more members of the HTG group have started to develop a more instrumentalist view of the atom, more than half remained true to a realist position. Irwin is disappointed by such a result, "The fact that over half the HTG should take the realist position is more disappointing given my efforts to establish the origins of the atom as an idea arising from natural philosophy" (p 21). He tempers these results by suggesting that the realist view is widely held (Solomon et al., 1992) and the results lead him to wonder about students' acceptance of other models in science. Irwin also claims that he is not encouraging his students to accept an extreme instrumentalist position but that he advocates a critical realist view (Hodson, 1986) which suggests we can be realist about some theories and instrumental about other (i.e., theoretical models). There are several problems with Irwin's views. First and foremost, I believe that the issue should not be one of realism vs instrumentalism. All of our scientific models have roots in the imagination of humans. As we begin to gather substantiative evidence, some of us adopt a realist view while others maintain a more critical view of the model's connection to reality. Whether you believe that atoms are real or that they are merely useful constructs, the fundamental query is still what makes us believe? It is a failure to address this question that seriously limits the usefulness of an approach like Irwin's. Ernest Mach was a famous physicist who adamantly opposed the idea of atoms and Ian Hacking, a famous Canadian philosopher, believed in electrons because he could "spray them". In either case, both scientists were able to address the phenomena produced by the atom and explain them in terms of an adequate model. Should we deny the philosophical stance of a Mach or a Hacking to students in our classrooms?

Irwin also strongly identifies with a Popperian view of science. In the student questionnaire he asks of predictive and explanatory theories, "which of these is taking the bigger risk?" and in his instruction he outlines how Mendeleev and Newland "risked censure from their fellow scientists", and how some theories are more speculative and more liable to refutation". Irwin readily admits that,

> "I told the group that Dalton made some highly risky assumptions such as his assumption that one atom of hydrogen combines with one atom of oxygen in the formation of water. This led to errors ... until Faraday electrolyzed water to discover that he ratio of H:O was 2:1" (p. 22).

First, his approach is one of teaching to the test, the answer he wants is the Popperian view that good theories take risks. The inherent problem with this approach is that Irwin's view (that is, Popper's view) of science is correct. Secondly, the assessment that

Dalton's explanation of how hydrogen and oxygen combine to form water is risky is made entirely in hindsight. It seems that Irwin takes a position that since Dalton's model was falsified, it was risky. However, to me, Dalton's explanation appears to more of an example of a scientist protecting his hypothesis. The volume ratio of hydrogen to oxygen in the synthesis of water was shown by Gay-Lussac in the early part of the 19th century. If one accepted Avogadro's hypothesis that equal volumes of gas contained equal numbers of atoms (molecules) then Dalton's explanation that water was HO was wrong. However, Dalton rejected Avogadro's hypothesis, and for good reason. The electrical nature of the atom was considered to be the potential source of the bonding of compounds and Dalton concluded that two oxygen atoms, being positive ions, could not bond together.

In spite of these limitations to Irwin's study, there are several interesting outcomes from this research. Even though time was spent on the historical perspective students performed equally well in the content post-test suggesting that the inclusion of a historical perspective does not take away from the time necessary to cover the content outcomes. Another interesting outcome can be found in the students' responses to the questionnaire. One question asks, "Are scientists ever wrong in their theories? Can wrong ideas in science ever be useful?" Students responses vary but in the FFG group 20 students (83%) answered "yes" without any elaboration or inappropriate elaboration. However, in the HTG group only 6 students (33%) answered without elaborating. Students supported their answer by suggesting that scientists learn from their mistakes and that wrong ideas lead to new ideas. This rather large discrepancy suggests that students in the HTG group were much more aware of, and open to the development of scientific ideas.

Perhaps some of the most interesting results of this study come from Irwin the teacher. Using the historical approach he found that it lent itself much better to introducing philosophical discussions, in other words, the curriculum was an enabler permitting such discussion to take place. In the class without the historical perspective as a required component, the discussions pertinent to NOS are never broached. However, after an initial reluctance, students in the HTG group welcomed the opportunity to participate in philosophical discussions and, in the focus group interviews, these students dominated the discussions. Irwin comments that "philosophical discussions seemed to form an integral part of class discussions with the HTG group." The classroom discussions naturally generated by the historical context included such diverse reflections such as "what constitutes scientific knowledge", "what are the standards of justification for such knowledge", and "how flawed theories might lead to advances in knowledge".

In their research, Carey, Evans, Jay, and Unger (1990) adhered to Hodson's (1988) claim that the standard science curriculum advanced an inductivist view of science. Additionally they supported the Nadeau and Desautel (1984) view that

> "current practice reinforces a "scientistic ideology', including naive realism, a tabula rasa view of the mind, a credulous faith in the existence of the 'critical experiment', and a belief that science bring us gradually nearer to the truth by a process of accumulation of facts". (p. 515).

They advocated that the inductivist epistemology be replaced by a constructivist epistemology and that students should be made aware that observation and experimentation are "purposeful, theory driven activities".

Carey et al. (1990) outlined the epistemological views of the young adolescents that guided their research. They cited a "remarkable consensus" concerning the stages that a learner passes through as they achieve a mature understanding of the world. Initially, young people make no differentiation between knowledge and reality and they believe that only ignorance reflects an incomplete understanding of the world. Later, young adults become aware of differences in beliefs and interpretations of similar observations. This awareness has the potential to be manifested in a form of radical relativism. Finally, some people, attain a more mature understanding that absolute truth is elusive and form an understanding of the relationship between beliefs and interpretive frameworks. The researchers focus on the early position of the learner as a naive realist as relevant to their interests in the understanding of NOS developed by 12 year old junior high students in an intervention study. They point out an insightful example from Kuhn and Phelps (1982) who studied 10 and 11 year old students experiments with chemical reactions. Kuhn and Phelps reported that students' methods were often unsystematic and that they often arrived a illogical conclusions. Observing student experiments with colour and chemical change, they commented on an all too common circumstance in the science classroom with students and their experiments:

> "The subjects commonly behaved as if their goal was not to find the cause of the colour change, but rather to produce the colour change. Just as children do not distinguish theory from evidence, they do not seem to

> distinguish between understanding a phenomenon and producing the phenomenon" (p. 516)

This lack of understanding the difference between theory and evidence is depicted as an important aspect of understanding NOS. Students, especially younger ones, have a great deal of difficulty thinking about a theory, including being able to suggest possible instances that could refute the theory.

Carey et al. developed a three week unit in which students formed and tested their own hypotheses about the role of yeast in bread making. Initially, the students participated in some activities which were used to promote thinking and reflecting on their own inquiry processes. These activities, advanced in a constructivist mode, encouraged students to speculate about the nature of life on Mars guided by the questions, what does "living" mean and "how do animals disguise themselves". Next, the students viewed a video of a "black box" activity in which Linus Pauling isolates and tests systematically the shape of an object in a closed opaque container. The students then began their exploration by considering the difference between bread and unrisen bread dough and confronting the causal question "What makes bread rise?" After identifying several factors the students propose hypotheses and controlled experiments in a systematic manner to support or refute the hypotheses. Experiments, including thought experiments, are performed and students find that the evidence is consistent with the hypothesis that yeast is alive. In a feedback loop to the opening lessons of the unit, the students are now challenged about the very nature of their beliefs of living things that they initially stated in their first lesson on speculating about life on Mars.

The research study was conducted with seventy-six students in a mixed ability grade 7 science class in a large city. The classes were taught by the regular classroom teacher and observations were made by research assistants. Twenty-seven students were selected for pre and post unit interviews designed to probe students' views on the nature of scientific knowledge and inquiry to determine if students moved beyond their initial epistemology. The questions from the interview were grouped into six sections:

1) nature/purpose of science/scientific ideas;
2) nature of a hypothesis; nature of an experiment;
4) guiding ideas and questions;
5) results and evaluation;
6) relationships.

The interviews were coded independently by two researchers and compared for agreement. Disagreements (26%) almost always involved only one level of difference and were resolved by discussion.

In their analysis, Carey et al. identified the responses from the students about the nature of science which ranged from the view that science is about discovering facts to constructing explanations about natural phenomena. The students' responses were coded as one of four levels. Level zero were students' answers which represented misconceptions, poor, or no understanding. In level one responses, the students did not differentiate between ideas and experiments. In these responses students typically state that a scientist "tries to see if it works" and the student is not clear if "it" refers to ideas, inventions, activities, or experiments. The students possess the view that the goal of science is to discover facts about the world and to invent things. In level two responses, the students differentiated between ideas and experiments. They acknowledged that the purpose of an experiment was to test an idea. Consequently, experimental data could lead to the revision or rejection of the idea. In this view, the goal of science is to understand how the world works. Finally, in level 3 responses, the students distinguish between ideas and experiments, as in level 2, but they begin to articulate that the goal of science concerns the construction of explanations about natural phenomena.

Overall, the mean score from pre to post interview for the 27 students increased, on average, one half of a level with a significance of $p < 0.001$. All students showed improvement with 16 students achieving an increase in response levels of 1.5 or better with 5 students achieving increases of 2.0 levels or better. In the pre-interview, no students had achieved a level of 2.0 or better. The greatest score increases were found the sub-sections on "Guiding ideas and questions, Results and evaluation, and Relationships, each with significance levels of $p < 0.001$. While students made significant gains moving beyond level one understanding they did not, as a group, approach a level 3 understanding. Carey et al. suggest that this means that the learning was genuine but that it remains an open question if these gains can be retained. Further, they recommend that more sustained curricular intervention could lead to a level 3 understanding and enhance retention. They also suggest that it remains to be seen if a students' gain in understanding of NOS impacts their conceptual development and learning of the science content.

A significant part of this study is the nature of the intervention. Learning was in context (the making of bread) and preliminary activities (characteristics of life, black box) were organized such that the teacher would return to them so that students could see how their own ideas have been challenged and changed. Additionally, the constructivist perspective helped involve students in more authentic activities. Finally, in the evaluation, the students were not required to choose either/or type of responses (as in earlier NOS assessment tools) but they responded freely. The researchers respected students's ideas and the fact that these ideas pass through several stages as we build a more sophisticated understanding of NOS. Knowing that a learner is level 1, or level 2, enables the teacher to plan interventions to first move students to the next level of understanding. It seems that few students "skip" levels implying that interventions must be sustained.

Finally, the researchers indicated that in future studies the levels of understanding must be better articulated. We may also consider that the delineation that needs to take place is within the aspects of NOS that we assess. The relationships between theories and evidence are complex and students may hold an understanding of a particular aspect about this relationship while maintaining a naive understanding of another aspect. For example, a student might believe that scientific theories are tentative and still maintain a belief that eventually a theory advances to a law when it is "proved". The problem that arises is that by further delineating these aspects of NOS, testing becomes overwhelming. In the future, we may need to begin to focus our research on specific characteristics of NOS without concern for accumulating an arbitrary score on a general understanding of NOS.

In another recent study, Schwartz, Lederman, and Thompson (2001) followed one teacher's experience with teaching science as inquiry in terms of developing the students' conceptions of NOS. The authors support a model of scientific inquiry that extends beyond the development of process skills such as observing, classifying, measuring, and analyzing data to include scientific reasoning and critical thinking necessary to develop scientific knowledge. Consequently, there is a natural and necessary interplay with many aspects of NOS including knowledge about the methods of science, design and interpretation of investigations, consideration of alternative explanations and models, and the differentiation between evidence and explanation.

Their study compared the effects of an inquiry based instructional approach, with and without explicit instruction on the nature of scientific inquiry, to students' views of NOS and scientific inquiry (SI). Explicit instruction in NOS was not included in the instructional sequence as the teacher believed that students would develop their ideas of NOS through inquiry methods. The study included four sections of an Integrated Science class (n = 115) who were taught six inquiry based investigations designed by the teacher. The investigations focused on process first and content second, and topics were chosen that would be of some interest to students. The topics included insect populations, germination of seeds, a comparison of different brands of paper towels, plant growth, bacterial populations, and chemical reactions. Two of the sections of students experienced a more explicit emphasis on SI through journal questions and discussions. The other two sections maintained a journal on scientific investigations only.

In the first week of school students responded to the questions:

1) What do you think science is?,
2) What do you think makes science different from other subject you study in school?;
3) What is involved in doing a scientific investigations?

Students responses were analyzed to provide an outline of their initial views and after the completion of the nine week unit, the students wrote the VNOS-HS and VOSI[107]. A total of twenty students, five from each section, were randomly chosen to be interviewed.

Schwartz et al.(2001) reported that the initial views of the students were consistent across the four sections and that the students generally viewed science as the study of the world or they perceived science as a subject they were exposed to in school. The researchers commented that "the students views of science were mainly limited to school-based science and they did not typically expand their thinking to science as an endeavor that creates the knowledge they learn about in school" (p 10).

The results of the VNOS and VOSI tests revealed that students generally held naive views of science and inquiry. The general tendency was towards an absolutist view of science and in the case where students held a more tentative view of science they held that any change occoured only in the context of an accumulation of scientific knowledge as the result of new information. Other less common views included the notion that science changes as the earth changes while a few students expressed a more informed view that science can change as we change our perspective or the way we look at the available information.

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107 Views on Scientific Inquiry. These tests are modifications of the VNOS-C (Lederman, Abd-El-Khalick, Bell, Schwartz, & Akerson, 2001)

Concerning theories and laws the researchers report that all students held misconceptions. Theories were seen as "guesses" or "opinions"that were tested until they were "true" and proven to be laws. However, students held inconsistent views on the proof conditions. For example, a typical response with respect to the relationship between theories and laws would be, "A scientific theory is something that can't be positively proven. A scientific law is something that is definite". Later, in interviews, students revealed that the use of the word proof was not always intended to be absolute proof but reflected a belief that there "was a lot of evidence" and "it happens all the time". Similar findings were reported in the Lederman and O'Malley study indicating that a complex opinion can be disguised when students provide quick response answers to seemingly simple questions. Consequently, the importance of using a paper and pencil test combined with an interview process versus relying on Likert-type or multiple choice tests is a critical issue in any further research. Also, it seems that what students believe is a tentative view of science does not necessarily match our understanding of a tentative view. Students are often able to adhere to a tentative view of science, that is, science changes over time but this view is often the result of our ability through technology to make more observations as opposed to any kind of change in perspective as we interpret data in new ways and with new models. This translates to a view that science is still "discovered" as opposed to a product of human creativity and imagination. Perhaps one of the reasons for our failure to adequately address NOS issues in science education lies in the fact that the theory-evidence-law relationship is a complex one with many variables. One suggestion is that we identify these complexities and begin to build lessons that address each of them more specifically. That is, initially we could begin to look at the parts instead of the whole. For example, students might consider just the source of a theory by addressing the question, "does a theory emerge from nature or do we explain nature?". In this way the student reflects on a simple question without being burdened by the complexity of the nature of theories. Over time the complex nature of theories could be developed into ever increasing levels of sophistication.

Schwartz et al. also reported a considerable range of student ideas concerning the methodology of science. The majority of students held views that indicated that experimentation requiring controls and variables were required for "proof" in science. On method, half of the students believed in a single scientific method. Once more, interviews helped identify a variation in reasoning among the students on scientific method. Students who answered "yes" to the question that there exists a single scientific method supported their answers in four different ways. They would:

1) list the traditional steps of the scientific method including hypothesis, control of variables, etc.,
2) they would list categories on the Inquiry Scoring Guide[108],
3) provide an open description such as asking questions and collecting information,
4) provide no information but claim they heard about it before and therefore there must be a single scientific method.

For students who responded "no", that is, they seemed to believe that there was not a

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108 The Inquiry Scoring Guide is a state designed guide for inquiry which lists outcomes for scientific investigations in terms of framing the investigation, designing the investigation, collecting and presenting data, and analyzing and interpreting results.

single scientific method, Schwartz et al. reported three types of answers in the interviews. The students would:

1) explain that there were experiments with variables and experiments that collected observations,
2) state specific cases as differences such as an insect study versus and bacterial study;
3) state very general differences such as some investigations are inside and some are outside.

The researchers also noted inconsistencies in the students responses, for example, some students outlined the steps of the traditional scientific method and then referred to an example which does not highlight these steps.

A large majority of the students (about 80%) demonstrated confusion between data and evidence. Data was often associated with numbers and evidence with physical objects. Some students related evidence to proof and most of the students failed to articulate the meaning of data analysis. Often students failed to recognize that the interpretation of the data was related to the original question and they saw data analysis more as a presentation of data in charts and graphs for one to view rather than for interpretation. Although a few students were able to recognize data analysis as a process by which the collected information is organized into patterns or explanations it is not all that surprising that students held an isolated view of data and analysis since these tasks are often taught as isolated experiences. For example, graphing data is just seen as another step in the scientific method. Other research (Roth 2002, Roth and Bowen, 1999) shows that students fail to make the connections between the actual event, the data, and the representation of the data on a graph.

Schwartz et al. identified two main differences between the explicit and implicit teaching groups. They report that students in the explicit group held more informed views of multiple methods of science and were less likely to associated scientific investigations with the traditional scientific method. Secondly, about 50% of the explicit group (versus 10% for the implicit group) recognized the role of subjectivity in the interpretation of data and that multiple interpretations could be influenced by differing perspectives, knowledge background, and scientific methodology.

The researchers concluded that the state of science education and science education reform is the same today as it was 100 years ago. They contend that we continue to achieve the "holy grail of in-depth understanding of scientific concepts" while failing to provide students with the critical organizing themes of NOS and scientific inquiry. We still expect that students, and their teachers, will come to know and understand NOS by simply doing science even though doing science through inquiry presents and promotes a rather naive view of science. The researchers strongly advocate for a more explicit form of NOS instruction that emphasizes that science is done by humans. They resolve that "without explicit attention afforded to relevant aspects of NOS and SI, even within the context of inquiry-based experiences, learners' views of NOS and SI will likely remain unchanged.

Summary - Research in NOS

There are several significant factors that the research in NOS reveals which are pertinent to this study. The limitations of the Likert-type tests mandates that an open-ended type of instrument be used to assess and gain an in-depth understanding of students' idea of NOS. Additionally, any form of pencil and paper assessment must be supported by follow-up interviews to validate and clarify students' written responses (Lederman & O'Malley, 1990). Consequently, Lederman's VNOS instrument was selected for the research. The VNOS is well supported in the most recent literature and the interview process provides an in-depth insight into the students' responses and, importantly, their reasons for believing.

The research indicates that students possess inadequate views of NOS and that they hold a spectrum of ideas about NOS. In some cases, the students' views seem developmentally appropriate. That is, they seem to hold a progressive notion that theories advance from ideas and educated guess to hypothesis (Griffiths and Barry, 1993). However, they also seem to extend these ideas to hold a view that theories advance to a fact or law status (McComas, 1996).

The research also indicates that teachers do not have an adequate understanding in NOS and that they hold eclectic views which influence their teaching in different ways (Brickhouse, 1990; Gallagher, 1991; Hodson, 1990). Additionally, their views experience constraints such as their academic preparation and lack of professional opportunity to study NOS. Consequently, it may be that the only opportunity for growth on the teacher's part is to be compelled to explicitly address NOS outcomes in the designed curriculum.

An explicit historical perspective (Ab-El-Khalick and Lederman, 2000; Irwin, 2000; Klopfer and Cooley, 1961; Solomon et al., 1992) has demonstrated some promise as an instructional strategy to promote a better understanding of NOS. However, longer time frames may be necessary to achieve a greater, and more permanent, understanding of NOS. One means of achieving this may be through the adaption of a constructivist perspective where activities are organized such that they may be revisited helps students' see how their ideas are challenged and changed (Carey et al., 1990). Finally, the Schwartz et al. (2001) study indicates that inquiry techniques, without explicit instruction in NOS, do not enhance students' understandings in NOS.

Chapter IV

Teaching and the Nature of Science

A Role for the History of Science

A role for the history of science promoting the nature and philosophy of science has been endorsed by historians and philosophers for many years (see Klopfer and Cooley, 1963, Lederman, 1992, Matthews, 1994, Russell, 1981, Winchester, 1989,). History of science is often used as a means to improve students' attitudes, interest in, and appreciation of science (Welch & Walberg, 1973), and to establish a "romance" between the discipline and the student. The benefits of a historical perspective include the spanning of the "two cultures," as portrayed by C.P. Snow (Stinner, 1994a), and the allure of "recapturing the experience of those who once participated in exciting events in scientific history" (Conant, 1970). It has also been suggested (Brush, 1974) that the teaching of the history of science can act to balance the naive view that science is a search for absolute truth and affords a more accurate characterization of the methods of science (Brush, 1989; Russell, 1981).

Science is a human activity and to pursue knowledge seriously demands an awareness of the work of your predecessors and the controversies surrounding their understanding. Copernicus and Galileo familiarized themselves with early ideas of cosmology and terrestrial physics before they completed their revolutionary contributions to science. They used an understanding of history to frame concepts, appraise conflicts, and to connect with preceding beliefs through thought experiments in a creative and critical thinking manner.

Although the history of science is often considered to provide a more humanistic view of science, some researchers have started to investigate a role for the history of science in conceptual development. Monk and Osborne (1997) proposed that the study of scientific concepts, well-placed in the context of discovery will help students because:

- historical thinking often parallels their own
- the now accepted scientific idea was often strongly opposed for similar reasons to those proffered by students; and
- it highlights the contrast between thinking then, and now, bringing into a sharper focus, theories nature and achievement of our current conceptions (p. 409).

Students' ideas have been demonstrated to parallel historical concepts (Wandersee, 1990) including some of the same preconceptions as the great scientists. Appreciating where great minds had difficulty is a potential comfort to students unsure and afraid to express their own viewpoints (Mathews, 1989). Students who perceive that electricity is a fluid, or that the atom is similar to the solar system, walk among giants. Today, a student who posits that electric current flows from the positive and negative terminals of a battery is said to hold a "clashing currents" misconception. In contrast, Barlow's corresponding representation of current in the 1820's gained the attention and respect of a broad scientific community (Caneva, 1974). We may not want our students to maintain such naive ideas but it does not mean they are illegitimate or necessarily wrong. We need to recognize that these initial ideas are the products of high-grade thinking and form conceptual stepping stones as we begin to formulate more sophisticated ideas of nature.

Many research studies suggest that students' initial conceptions in physics differ substantially from those found in scientific theory (Clement, 1983; Hestenes, Wells, & Swackhamer,1992; McCloskey 1983; McDermott 1984). These studies also suggest that early conceptions can be extremely tenacious and highly resistant to instruction. A concern with these factors has motivated science educators toward a theory of conceptual change. The research in cognitive science has recognized the importance of prior knowledge in a learner's conceptual development (Ausubel, 1968) and many investigators have pointed to the intriguing parallels between a student's conceptual development and the historical development of scientific ideas (Piaget 1970, Nersessian 1989, Clement 1983). Some researchers have offered models of conceptual development that suggest conceptual change imitates the scientific practices of normal and revolutionary science (Posner 1982), and others have described extensive theories relating ideas in science, history, and psychology (Piaget & Garcia 1983). Science educators hope that understanding the processes of conceptual development in science and their relationship with the context of discovery will reveal important information to help students construct their own understanding of difficult and often abstract representations of our world.

For Piaget, knowledge was about change and transformation. Moreover, he felt that cognitive structures, in the course of being used, also changed. Piaget rejected a static epistemological viewpoint and believed that knowledge was perpetually in a state of evolution. For Piaget (1970), knowledge today was just a snapshot in time, changing to its present state, and continuing to change in its future state. He asserted that,

> "The current state of knowledge is a moment in history, changing just as rapidly as the state of knowledge in the past has ever changed and, in many instances, more rapidly." (p. 2).

The hypothesis that conceptual development parallels historical developments is also held by other educators, historians, and philosophers. Thomas Kuhn compares Aristotle's views with those of "naive" learners,

> "Today the world view held by many adults shows few important parallels to Aristotle's, but the opinions of children, of the members of primitive tribes, and of many non-Western peoples do parallel his with surprising frequency." (Kuhn, p. 96).

Research in science education reveals many domains in which students experience preconceptions and have difficulty understanding scientific explanations. These studies cover a wide range of topics like electricity (Shipstone, 1985; McDermott, 1992), heat and temperature (Erickson & Tiberghien, 1985), conservation (Driver, 1985), photosynthesis (Wandersee, 1986), and matter in a gaseous state (Sere, 1985). Many investigators are beginning to use these identified areas as a basis for a historical analysis. Some parallels with the historical model that have been suggested, but not fully developed, include light (Guesne, 1985), the particle nature of matter (Nussbaum, 1985a), and concepts of the earth (Nussbaum, 1985b). Driver, Guesne, and Tiberghien

(1985) urge some caution with the seductive nature of historical analysis and suggest that children's ideas are not always part of a coherent system. However, some specific domains, other than mechanics, are beginning to articulate more clearly a comparison between historical and conceptual models. (Wandersee, 1985; Wiser & Carey 1983).

In a constructivist environment, the studying of the history of pre-scientific ideas should also position teachers to understand better and help children in their conceptual development. The history of science permits us to trace the growth of knowledge within a discipline and provides a context from which the teacher and student may view knowledge as we represent it today. Ultimately, we hope that any research in cognitive development will have a positive impact on instruction. Spontaneous reasoning, alternative views, preconceptions, and resistance to conceptual change are all areas that we need to examine more carefully. Students often present alternative views and the history of ideas provides a context from which we can respect these views. The student who holds that electric current originates at the both the positive and negative terminals of a battery and clashes at a bulb, or the student who contends that impetus cumulates in acceleration, walks in good company historically. If history of science can be used to predict students' misconceptions, learning difficulties and patterns, then teachers can plan appropriate instructional experiences (Wandersee, 1985). Moreover, the history of science can reveal useful steps in conceptual development like the thought experiments and idealizations of Galileo. Other experiments and demonstrations, like Faraday's discussion of a burning candle in a closed container, can help initiate instruction with anomalous results through discrepant events.

Our knowledge of conceptual change in the history of science, and the nature of these changes and processes, strengthens our understanding of our students' intellectual struggles. This understanding should facilitate the formation of innovative instructional strategies to mediate these struggles in a constructivist environment. To these objectives, conceptual developments in the history of science should play a critical role helping us to understand our students and to formulate our teaching practices. In the future, we look to the establishment of a research agenda in this emerging field.

Russell (1981) reminds us that much of the research surrounding the use of history of science in science education is inconclusive and although there are positive results "it appears that historical material *does not ensure* improved understanding of science (p 61). However, Russell is not willing to deny a role for the history of science arguing that "if we wish to use the history of science to influence students' understanding of science, we must ... treat historical material in ways which illuminate particular characteristics of science" (p 56). To this Abd-El-Khalick (1999) adds "HOS of itself may not suffice to improve learners' views of science. Aspects of the NOS that are deemed important for students to understand need to be given *explicit* attention" (p. 242).

In this thesis the history of science is integrated with standard curriculum outcomes to explicitly address specific NOS outcomes.

A Role for Inquiry and Constructivism

Inquiry-based learning has its roots in the curriculum reform movement of the 1960's. In 1959 Jerome Bruner (1960) convened the Woods Hole conference which provided a focal point for major curriculum reforms in the United States and abroad. The conference was a response to a "long range crisis in national security" and consisted of thirty-five scientists and educators intent on shaping education. A significant outcome of these revisions was the development of a plethora of publications and curriculum reforms based on "discovery" or "inquiry-based learning" methods.

Inquiry-based learning focusses on science process skills, it emphasizes hands-on activities favouring observation, classifying, measurement, and controlled experimentation using independent and dependent variables. Such instruction formed the cornerstone of the curriculum reforms of the 1960's and introduced "hands-on" activities to science education. Inquiry methods more closely integrated the lab activities with instruction and a greater emphasis was placed on cognitive skills and processes of science. Educators often called the teaching style "guided discovery." The teacher facilitated the students' actions as they performed the same tasks of discovery that some real scientists might use. While the emphasis was purportedly on process, the result always converged to content. Students followed "recipes" to complete labs and memorized facts and laws to reiterate on tests. In the classroom, inquiry methods became traditional laboratory methods in disguise.

Today, the dominant mode of instruction remains the strict empirical design, partially integrated into a lecture-laboratory style of instruction. Yager (1992) reports that

> "For most students science becomes what is printed in textbooks and what is included on associated worksheets and in verification-type laboratories." (p. 906).

In the lecture-laboratory style the laboratory exercise illustrates the information outlined in the classroom lecture. The lecture includes the definition of terms, characteristics and behaviour of phenomena, and derivation of equations needed to solve for some unknown quantity. In the laboratory, procedures are written in worksheets that detail each step to guarantee the experiment will work and reveal the "correct" result. All of the students do the same exercise, on the same apparatus, in the prescribed manner, to arrive at the same conclusion. This teaching style emphasizes the verification of scientific laws. Even though the student knows the outcome before they do the experiment, the experiment "proves" that the laws are correct.

A significant problem with the lecture-laboratory approach is the failure to make intended connections to theory and practice. Teachers often regard the laboratory experience as a separate endeavour whose only connection to the theoretical is verification. Typically, the laboratory is separated from theory and the experiments are often done in an arbitrary sequence. The hands-on emphasis of inquiry-based learning seemingly implies that all work in science results from independent experimentation.

The problems of inquiry-based learning led educators to critically examine many of the principles and practices of inquiry-based learning. The motivation and justification of discovery learning was unclear as students were led to inevitable outcomes by a proposed recipe for success. They were never challenged to employ any skills they learned by developing and evaluating their own ideas, there was not enough time to pursue individual interests, and students rarely spontaneously proposed their own ideas about the physical world. Many science educators began to propose that the inductive mode of inquiry-based learning be replaced by a constructivist epistemology.

Constructivist-based learning can be summarized by two fundamental principles, the first pictures learners as active participants in the construction of their own knowledge. The second principle outlines the view that there is no universal reality, that is, we do not find truth about the real world but each individual constructs his own view from experiences. Moreover, the first principle, based on the findings of cognitive science, is generally accepted in the classroom, in fact, many teachers will claim they've held this attitude for years. Students do not come to school "tabula rasa", that is, as a blank slate, an empty vessel to be filled with predetermined scientific knowledge. They cannot passively receive information, our communication, words, and concepts cannot simply be downloaded to the student.

The second principle implies that there exists a uniquely constructed reality for each individual, in the extreme position, multiple constructed realities. It rejects realism of theories and the entities they propose for relativism and multiple meaning. The process of observation, key to inquiry-based learning, becomes problematic for the constructivists' view that the learner interacts with the environment and therefore is part and parcel of that environment. The act of observation alters what we see and objectivity is impossible, all knowledge is subjective.

Most teachers readily accept the first principle of constructivism that students must be active learners. They eagerly call themselves constructivists, engaging their students in hands-on kinds of activities. A gap, however, exists between the theories of constructivist-based learning and the practice of constructivist-based learning in the science classroom. Most hands-on activities that teachers organize for their students tend to be inquiry or discovery type activities. Consequently, what is claimed to be constructivist teaching must be seen as inquiry-based learning in disguise and therefore merits all of the associated criticisms. In other words, simple constructivist-based learning degenerates to inquiry-based learning which paints a naive view of the nature of science.

I have assumed the position that inquiry-based inductive methods depict a naive view of science. Also, I contend that constructivism based on the principle that learners actively construct their own knowledge, in practice, degenerates to inquiry and consequently, naive views of science. However, it is not my intention to dismiss either inquiry-based learning and constructivist-based learning. Both theories have made important contributions to science education. Inquiry-based learning began an assault on the traditional teaching practices of lecture and presentation, while constructivist-based learning has been extremely successful articulating the role of the learner.

One possible means to deal with the problems and criticisms associated with inquiry is to re-consider inquiry in light of its original intentions. Inquiry has its' roots in C.S. Pierce's work (McMillan, 2001) who stressed that inquiry should begin with an anomaly or some form of judicious skepticism and through the processes of abduction, deduction and induction arrive at an understanding of some tentative scientific principles (Siegel & Carey 1989, p 23 - 26). Pierce's view of inquiry is one of generating and refining of knowledge unlike the prescriptive form of inquiry we find in practice today.

Schön (1992) adds that "the inquirer does not stand outside the problematic situation like a spectator; he is in it and in transaction with it. Both doubt, and its resolution, are transaction properties of a continuing and inherently open-ended relationship between the inquirer and the situation". (p. 122).

Schwab (1962) called for the teaching of science as enquiry instead of merely conveying the traditional "rhetoric of conclusions"[109] commonplace in science textbooks. Further, McMillan reminds us that Schwab wanted teams of students to encounter phenomena, discuss possibilities, debate the feasibility and validity of different problems, consider methodologies, apportion responsibility, write reports, account for and resolve discrepancies, and arrive at consensus.

Gerald Rutherford (1964), one of the original authors of the Project Physics course which emphasized the history of science, differentiated between two forms of inquiry. Inquiry as technique, commonplace in school science, was described as "using the method of scientific inquiry to learn some science". Rutherford outlined inquiry as content as "operating on the premise that the concepts of science are properly understood only in the context of how they were arrived at and of what further inquiry they initiated (p. 81). He held that "To separate scientific content from scientific inquiry is to make it highly probable that the student will properly understand neither" (p. 84). He also cautions that progress toward teaching science as inquiry will remain unsuccessful if teachers do not cultivate an understanding in the history and philosophy of science.

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[109] "the rhetoric of conclusions" is the means by which we are presented science in its completed form. That is, as literal and absolute truths without evidence or reason why we believe.

The position that I would like to advocate is that HDCM be used to promote inquiry as it was intended to be. I believe that in part, a means to address the original intentions of inquiry, in particular Rutherford's view of inquiry, may lie in emphasizing the historical re-constructions of conceptual models. Students can become active participants in their own inquiry by designing their own tests to move from simple, tentative, early models, such as Plutarch's early model of electricity to more sophisticated and predictive ones like the particle model of charge. Further, it is argued that this type of approach will address the problems of teaching and understanding the nature of science that have plagued us for years. That is, the failure to introduce aspects of NOS explicitly into the curriculum. In this manner, HDCM is intended to integrate science content with science inquiry using a historical context.

Teaching the History of Science

Although educators and curriculum developers agree that the nature of science is a valuable goal in science education, research indicates that we have not achieved these goals. It has been suggested that the history of science can play a role in science education by promoting instruction in the nature of science. However, it is one matter to advocate a role for the history of science and another to implement teaching the history of science. Some researchers (Gallagher, 1991; Monk & Osborne, 1997; Solomon, 1992) have suggested that we lack resources and methods to incorporate the history of science into regular science instruction. These concerns raise a number of significant questions including "What role does the history of science play in addressing the NOS in science education today?" and, "What do the supporters of history of science propose as useful models of instruction for integrating the history of science"? Cawthorn and Rowell (1978) suggest one way to explore a subject as presented in schools is by analysis of the contents of textbooks in popular use. Since textbooks are written in consultation with teachers, and since the majority of teachers use the textbook most of the time (Yager, 1983), we can anticipate that the point of view of the text closely resembles the delivered curriculum in the classroom. Brackenridge (1989) reminds us that many educators, from high school to graduate school, search for a good text to present a self-contained course. Many teachers parallel the content of the text, and the text becomes the source for class work, laboratory work, and homework activities, as well as, a basis for evaluation (Gallagher, 1991). In textbooks today, the exposition of history ordinarily assumes three forms:

a) Vignettes,
b) Confrontations, and
c) Heroes of science.

Briefly, I will examine each form and offer some alternative views to using these modes of representing the history of science in science instruction.

<u>Vignettes</u>

Interestingly enough, most persons when asked to recall their high school science experience can refer to the Eureka! experiences narrated in texts. The tale of

Archimedes' bath, the apple falling on Newton's head, or the experiments of Galileo atop the Leaning Tower of Pisa, are examples even the most disconcerted science student can easily recount. While seemingly trite, and often untrue, these vignettes of history suit certain pedagogical needs as we try to initially attract students' attention. Some of these vignettes provide interesting narratives, and we can also use them in textbooks to promote specific issues such as women in science, or environmental concerns.

Research also supports the use of the narrative. Lederman and Druger (1985) reported that the greatest change in students conceptions occurred with teachers who displayed positive characteristics like frequently using anecdotes to promote instruction and establish rapport with their students. Shrigley and Koballa(1989) suggest that the usefulness of anecdotes in other venues could be transferred to the science classroom. They point out that

> "Savvy writers sell their books as much on their anecdotes as on their data, popular banquet speakers tell good stories, and advertisers use anecdotes to sell their products. Science teachers should also take advantage of the power of anecdotes." (p. 297).

While vignettes in science textbooks may distort history, the significant problem, at least for story telling, is not so much the accuracy of the yarn, but the fact that the narratives have become a token to history in textbooks. They are few in number and remain confined to sidebars of the page isolated from the relevant science content. One way to bring the vignette out of the textbook and into the classroom is to involve the teacher and/or the student in writing the vignette.

Wandersee (1990) proposes that such connections with the past can make science learning more meaningful and he employs Egan's (1986) model of story form to develop his own vignettes for the history of science. The three steps of Egan's model are:

(a) Identify an important event and apply it to a character from the history of science;

(b) Find binary opposites, in characters or events to frame a dramatic conflict;

(c) Resolve the dramatic conflict and apply the story to today's world.

For example, Wandersee draws upon the story of Antony van Leeuwenhoek, choosing Leeuwenhoek's preoccupation with secrecy to frame a binary pair (concealing vs revealing research findings). The story, whether concealing information stifled or advanced development of his microscopes, is resolved by considering some aspects of the period such as the language of communication (Latin) and the nature of intellectual property. Discussion concludes with a consideration of potential applications to modern science.

In the HDCM unit developed for this research, teachers were encouraged to let students investigate the early period of chemistry portrayed by the alchemists and write on the "day in the life of an alchemist". One group, went beyond the traditional mode of storytelling to write and produce video segments for a day in the life of an alchemist.

<u>Confrontations</u>

The confrontations and conflicts of science possess great potential in developing the views of the nature and philosophy of science. However, textbooks feature them only in a winner/loser scenario with the "correct" theory replacing the obviously wrong one. Consider how we depict the great Aristotle in textbooks,

> "Greek philosopher Aristotle claimed that an object falls at a speed proportional to its weight. This false idea was held to be true for more than 2000 years because of Aristotle's compelling authority." (Hewitt, 1993, p. 8).

We usurp and cast Aristotle's "false notions" aside with no discussion concerning the significance of the context in which he makes his claim. But a vacuum was not part of the Greek's world view and Aristotle considered his objects to be moving through a medium that could provide resistance. In modern terms, this is similar to a contemporary Stokes theorem problem (Stinner, 1994b). The speed of an object falling through a resistive medium, like a marble falling through a glass of oil, is proportional to the force (gravity) and inversely proportional to the viscosity of the medium. Was Aristotle wrong? In light of the fact that he had foreshadowed a theory proposed many years later perhaps we should judge Aristotle's physics differently. However, according to textbooks, Aristotle is "obviously wrong".

Galileo's confrontation of Aristotle's ideas of motion are also often represented as a revelation when he observed that two objects, dropped from the Tower of Pisa, reached the ground at the same time.

> "On one occasion, Galileo allegedly attracted a large crowd to witness the dropping of a light object and heavy object from the top of the tower. Legend has it that many observers of this demonstration who saw the objects hit the ground together scoffed at the young Galileo and continued to hold fast to their Aristotelian teachings". (Hewitt, 1993, p. 20).

The implication is that the objects Galileo dropped hit the ground simultaneously. Actually, the account of Galileo's experiment from the Leaning Tower of Pisa, as a refutation of Aristotle's ideas, is distorted. Although the experiment of dropping unequal masses was often performed , it is not likely Galileo dropped the objects from the Leaning Tower of Pisa (Cooper, 1935). Galileo lectured at the local university and commented in his writings and letters about the experiment. Interestingly, in the experiment from a high location, the masses will not hit the ground at the same time, and Galileo never denied it. In fact, he likely made his greatest conceptual leap because of this anomaly. Commenting in his *Two New Sciences,* Galileo recounts

> "Aristotle says, "A hundred-pound iron ball falling from the height of a hundred braccia hits the ground before one of just one pound has descended a single braccis. I (Galileo) say that they arrive at the same time. You find, on making the experiment, that the larger anticipates the smaller by two inches; that is, when the larger one strikes the ground, the other is two inches behind it. And now you want to hide, behind those two inches, the ninety nine braccia of Aristotle, and speaking only of my tiny error, remain silent about his enormous one". (Drake, 1974, p. 68).

While Cooper has questioned Galileo's reference to Aristotle, the great achievement of Galileo is a conceptual leap from the real world to the ideal world. He no longer perceived the times the two masses fell as slightly different, he started to see them as nearly the same. The confrontation is most effective when it is not presented as "good" science replacing "bad" but when the evidence and challenges of both camps interplay. In such an interplay, we would illustrate that Galileo seizes Aristotle's ideas and extends them further in a thought experiment to support his own view. Galileo

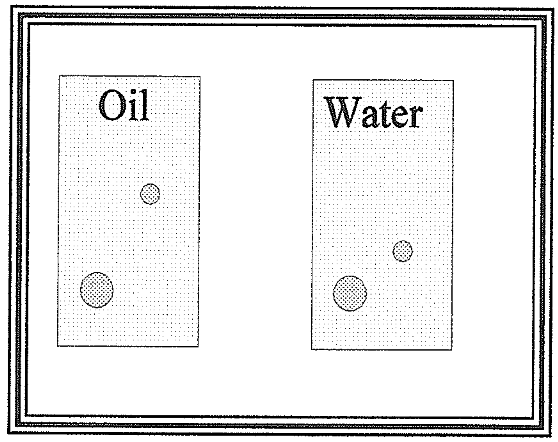

Figure 9

argued that if we consider two objects of different masses that fall in different resistive mediums, that the heavier body does fall faster. If the mediums become progressively thinner, the differences become less and less, ultimately if we extend this to a vacuum they would logically fall at the same rate. We can easily demonstrate this by dropping two different sized marbles in a medium like oil (figure 9) and then repeating for a less viscous medium like water. We can then ask students to extrapolate the experiment to increasingly thinner mediums until they approach Galileo's idealization. The textbooks fail to describe these intermediate positions and critical transitions in favour of a description of "right" or "wrong" science.

Schoolbooks often echo confrontation as the replacement of one theory with another. Copernicus and Ptolemy (astronomy), Galen and Harvey (circulation), and Lavoisier and phlogiston theory are but a few examples of conceptual developments and high grade thinking lost to a perception of "defective" science. Scientific developments involving significant conceptual change in the history of science provides a unique opportunity to discover how models and theories become threaded into a more coherent fabric of ideas. Students should be a part of this development, we should let them be "phlogistonists" or "fluidists", participate in a debate, or role play the confrontation in the times and minds of the great scientists. For example, in the HDCM unit designed for this research, students investigate the decomposition of sodium chlorate using the phlogiston model. That is, during combustion a substance called phlogiston is liberated. In this experiment, when sodium chlorate is heated,. a gas is given off and collected by displacement of water. Students determine that the mass of the sodium chlorate has decreased because phlogiston is given off and the phlogiston model is confirmed.

In their next exercise students heat copper dust. In this experiment, the copper combines with the oxygen in the air to form copper oxide and the mass of the original contents increases. The students are now challenged to explain these results using the phlogiston model. In order to explain their results in terms of the phlogiston model students must conclude that phlogiston has positive mass sometimes and negative mass other times. The model is now becoming complicated and the students begin to look for other solutions. Lavoisier's experiments with respiration and combustion are described and a new model is advanced. The confrontation between phlogiston and oxygen, and Lavoisier's work and Priestley's work is considered in light of such specific aspects of NOS as models, laws, and theories, the tentativeness of science, and the characteristics of a good theory.

Heroes of Science

The third mode of expression of history of science we find in science textbooks is the presentation of the great discoverers or heroes of science. These "discoveries" of science dominate history in science textbooks. Newton's discovery of gravity, Oersted's discovery of electromagnetism, and Thomson's discovery of the electron, are but a few examples of an image of science represented as a defined path from observation to theory. This mode of presentation provides a conceptual economy for many principles and laws in science education but neglects the conceptual struggle that faced and challenged some of the greatest minds in science. The ideas of science do not consist of fortunate discoveries, they involve intellectual struggles and conceptual leaps, a transfer of ideas from generation to generation, and an intervention that embraces the nature and philosophy of science and scientific knowledge. Content, curriculum and instruction, and pedagogies rarely grant any attention to epistemological considerations. The history of science as presented in textbooks is typically a compendium of names, dates and their associated discoveries. Meanwhile, the most useful aspects of the history, the conceptual developments and evolution of ideas, the context and values of individuals remain clothed in secrecy in the annals of scientists, philosophers and historians. As a result, the dissemination of scientific knowledge becomes fragmented and isolated from the processes, values, and constructs of its practitioners, past and present.

Significant problems exist with the "who discovered it" history of textbooks. The most significant is not so much the omission of a vignette or heroic tale but the lost opportunity to transform a historical development of conceptual ideas into a legitimate and effective pedagogy to develop scientific content as well as probe the nature and philosophy of science.

In the HDCM unit, heroes of science (like Dalton, Thomson and Rutherford) are portrayed in a historical context which usually involves confrontation and competing models and theories. Students are asked to consider these ideas for their creativity and imagination, their explanatory powers, and for the events discrepant to each individual's ideas. In this way, students often have the opportunity to lay their ideas alongside the ideas of the great scientists and to appreciate the paths and pitfalls experienced during the great discoveries in science.

History of science as tendered in science textbooks is mostly a distorted view of history at best, a compendium of fabrications, names, and dates. A quick review of the index of a popular physics text reveals one hundred and thirty citations of historical figures which reads like a Who's Who of science beginning with Ampere and ending with Zweig. Unfortunately, the citations only refer to who discovered what, and when. This form of presentation provides an economy for many of the principles and laws in science but neglects the conceptual struggles which challenged men and women for many centuries and continues to challenge our students today. The interpretation is "Whigish," that is, we view history in terms of present ideals (Brush, 1974). Monk and Osborne note that "Such textbooks are written to provide students with the popular, contemporary, cleaned-up pre-justified accounts of the behaviour of the natural world". (p. 406).

Since it is unlikely that teachers will be willing to part with the modern version of the textbook, resources in the history of science need to be developed to go beyond the treatment of the history of science as related in the textbook. One way to extend the depiction of history of science in science textbooks has been advanced by Stinner, McMillan, Metz, Jilek, and Klassen (in press, 2002) who outline seven units of historical presentation in science.

<u>The Units of Historical Presentations in Science</u>

Stinner et al. prescribe a set of "units" of historical presentation that includes approaches which can be used by the teacher in placing science in context with the history of science. Their list not only includes the aforementioned vignettes and confrontations but adds case studies, thematic narratives, dialogues, and dramatizations.

Case studies are described as historical contexts with one unifying idea such that the scientific ideas of the historical period are presented, empirical support is gathered for the central ideas, and then diverse connections are made to extend the ideas beyond the story-line. Stinner et al. also use thematic narratives to identify general themes that transcend individual disciplines and link major activities in the various domains making humanistic connections. For example, the thematic couple of atomism and continuum "played an important role in shaping the conceptual structure of early twentieth-century biology and science" (Jordan, 1989). Other suggested themes include conservation, time, regularity or evolution, some of which might be connected by several small case studies to produce a continuous narrative.

The dialogue format presented by Stinner et al. is used to dramatise science. Raman (1980) also advocates this form of historical presentation writing "The method I discovered recently was to present the relevant information and ideas in the form of a dialogue in which the original scientists are made to speak of their ideas and theories" (Raman, 1980, p. 580). In this context, Stinner et al. also include dramatization, modern or home-spun plays that have been written about science and scientists. As mentioned earlier, one group of students in this study sought to dramatise the day in the life of an alchemist through video dramatisation.

In presenting their historical units, the authors recommend a "story line" approach to the teaching of science similar to the views of Arnold Arons. Arons (1989) argued that these stories could take the form of small versions of Conant's (1957) case histories "that can be infused into introductory courses, without seriously affecting the amount of physics being covered" Stinner (1994a) also believes that a science curriculum "should be humanistic, context-based, and well connected to a sound theoretical structure" (Stinner, 1994a) and can be adapted for all grades from the early years to university. For early years (K- 4) they recognize, respect and build on children's early conceptions, using motivating contexts that involve an exciting story-line and employ a number of first hand experiences. These activities are guided by a sound conceptual development model where teachers act as facilitators helping children build domain-specific knowledge and scientific reasoning in accordance with children's prior experience and thinking using scaffolded instruction. (see Fraser & Tobin, 1998; Glynn & Duit, 1995; McGilly, 1994; Minstrell & van Zee, 2000; among others). In the middle years the stories and contextual activities are followed by contexts that will motivate the students. Later, it is suggested that since many science teachers already use themes such as the particle nature of matter or the wave-particle nature of light that case studies discussing one main idea and/or experiment thematically are especially well suited to the senior years. Finally, for the post-secondary science classroom, Stinner et al. advocate large scale discussions around extensive well crafted contexts that do not shy away from detail and mathematical complexity.

Monk and Osborne's Model

Martin Monk and Jonathon Osborne are science educators who also support the integration of history of science into science instruction. They are motivated by the failure of the message to reach the teachers and they remain concerned that previous efforts for the inclusion of history of science have ignored teachers. Instead of the history of science being supplementary, as the vignettes from textbooks usually are, Monk and Osborne (1997) advocate that historical views be placed alongside students' ideas for consideration as alternative perspectives forcing students to compare and contrast different interpretations, raising the questions "how do we know?" and "what is the evidence for?" These alternative perspectives also permit the teacher to tap into students' prior knowledge respecting their ideas and building on a contructivist perspective.

Monk and Osborne present a model which begins with the teacher introducing a problematic phenomenon, such as "where do plants get their food from?", that was previously considered by earlier scientists. In phase 2 of their model, students' ideas and theories about the phenomenon are solicited using common strategies such as concept maps or brainstorming discussions. Such strategies encourage small group work and invokes a constructivist pedagogy which allows students to orient themselves to the phenomenon and become consciously aware of their own ideas (Driver & Oldham, 1985).

In phase 3 of this model multiple inputs of historical information might include:

- an example of early thinking on the phenomenon as yet one more view to consider;
- background information on the economic - social - political conditions of the time;
- an example of competing ideas from other scientists and not necessarily the modern textbook version;
- some discussion or exploration of the data or other background that might have added support for the historical view; and
- a brief chronology in terms of dates and events that needs sorting (p 416).

Monk and Osborne also advocate the use of a story-line and a carefully crafted vignette and argue that "the history of science will only be adopted by teachers if there is at hand material that is brief and easily assimilable"(p 417).

In their next phase students design tests to decide which version of explanation is correct and progress towards a consensus. The students act as a community of scientists reviewing each others ideas as they think creatively and critically to solve problems. The teacher uses appropriate judgement to decide if tests are feasible and which ideas lend themselves to further investigations. Ultimately, if necessary, students are guided towards modern experiments to provide evidence for modern interpretations. The scientific view is then introduced in the next phase as the modern version of explanation. Finally, in the Review and Evaluation phase students consider the implications of the evidence through additional class discussions and small group work. Monk and Osborne conclude that the history of science will continue to be "more talked about than taught" as long as efforts continue to focus on materials do not address the needs of the classroom teacher.

Historical Development of Conceptual Models

In this research study I have developed a curriculum unit which is based on the historical development of conceptual models (HDCM). This unit is compatible with inquiry and constuctivist views and explicitly addresses several aspects of the nature of science.

Gilbert & Boulter (1995) define a model as a representation of an idea, object, event, process, or system that can be expressed in many different ways (as diagrams, physical models, language). Thus, conceptual models are derived from the properties of things which are not directly perceptible and we use them to assign a cause where one is not apparent or observable. The defining properties of things like heredity, light waves, and gas laws help us form conceptual models to represent and explain such phenomenon. We infer and build imaginative models that connect our experiences and observations with scientific theory. Models, therefore, hold a position between these observations and scientific theory.

The inclusion of the historical development of conceptual models naturally promotes a better understanding of the nature of science. In general, models are viewed as more tentative than theories or laws (Kipnis, 1998; Machamer, 1992). Additionally, the contributions by many individuals over time, portrays science as a more humanistic endeavour, marked by intellectual struggles, and personal and cultural influences. In this sense, we move from the naive view that textbook models are an exact replica of nature to the view that models are products of human creativity and imagination. Justi and Gilbert (2000) also suggest that the development of historical models outlines a more authentic understanding of the philosophy of science. They propose a Lakatosian view of science using questions such as "how does the model overcome explanatory shortcomings of its predecessor or competitor?", to focus attention on degenerating or progressive research programmes. The conceptual development of models and theories in a historical perspective can also lead to a more accurate characterization of the methods of science and gives students an opportunity to place their ideas alongside the thoughts of great men and women.

Gilbert and Osborne (1980) claim that models enable concentrating study on special features of a phenomenon and that models can be used to stimulate investigations by supporting visualization of the phenomenon. However, aside from focusing our attention on the phenomenon, incorporating models in our instruction is also compatible with modern learning theories for cognitive development. Posner, Strike, Hewson, and Gertzog (1982) make an interesting connection between Piaget and Kuhn in terms of cognitive development and the philosophy of science. Posner et al., building on Piaget's work, began to formulate a view of how a learner's current knowledge interacts with new, incompatible ideas. They advanced a general pattern of conceptual change which is guided by the philosophy of science.

Conventional philosophy of science suggests two means by which we work with and recast our theory. The first is adherence to a group of central commitments as described by Kuhn's (1962) "paradigms" or Lakatos' (1977) "theoretical hard core".

These commitments define problems, guide solutions, and provide an organizational background for research and development of scientific knowledge. The second phase of theory development in science modifies these central commitments. If current inquiry does not fit within the accepted paradigm or hard core, then the basic assumptions must be altered in a "scientific revolution" or a "change in research program".

The fundamental position of Posner et al. is that there is a parallel development in the learners conceptual change through the processes of assimilation and accommodation[110]. In assimilation, students use existing concepts to deal with new phenomena. If existing concepts are inadequate, the learner must replace or re-organize central concepts in a more radical form of conceptual change called accommodation. Assimilation and accommodation are to conceptual change in a student as Kuhn's normal science and scientific revolutions are to conceptual change in history. Posner suggests that "accommodation will be a gradual and piecemeal affair" as students are not likely to have a clear understanding of any given theory. This means that if our objectives for teaching are major conceptual change, teaching strategies should include instruction to create cognitive conflict like a Kuhnian crisis. Therefore, like a Kuhnian revolution, students will seek resolution to their cognitive conflict through accommodation.

Kuhn's *Structure of Scientific Revolutions* (1962) seems to guide Posner's questions pertaining to accommodation. He is concerned with the conditions under which accommodation takes place, that is, when the learner replaces one central concept

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110 Although Posner et al. borrow Piaget's terms, assimilation and accommodation, they assert that this does not mean commitment to Piaget's theories.

by another. Current philosophy outlines that the acceptance of one theory over another entails more than just empirical verification, it also requires epistemic values like consistency, plausibility, and fruitfulness. Posner et al. give four conditions that must be met for accommodation to occur:

1. There must be dissatisfaction with existing conceptions.
2. A new conception must be intelligible.
3. A new conception must appear initially plausible.
4. A new concept should suggest the possibility of a fruitful research program.

First, unless students experience some form of dissatisfaction, they are not likely to replace the old conception with a new incompatible one. Posner et al. identify a major source of dissatisfaction as the anomaly which persists when assimilation is not possible. Posner suggests that this is an important aspect of instruction and

> "The search for instructionally viable and effective anomalies is of primary importance if accommodation is to be taken seriously as a goal" (p. 224).

In this study, Posner et al. point out that there was little evidence that anomalies in the learner existed. In the classroom, discrepant events are useful ways to create an anomalous situation. For example, if we balance some copper dust on a scale and ask students to predict what will happen if we burn the dust, most suggest that the scale will tip indicating that the pan with the dust gets lighter. When the dust is burned and the scale tips to indicate that the pan is heavier, an anomalous situation is created and an investigation begins to examine different explanations.

A concept is intelligible if it makes sense and plausible if it is believable. It is possible for a concept to be intelligible but not believable. Posner uses instruction in Einstein's special theory of relativity as an example of a new concept which can be intelligible but remain implausible to many students. By refusing to reject the notion of absolute space and time the student fails to assimilate the theory into an existing conceptual structure. In this sense, major conceptual change is not possible. Additionally, Posner et al. assert that the new conception needs to be fruitful and provide new insights, discoveries, and diverse connections. That which is fruitful to the learner can often be exposed by making diverse connections through the history of science.

Posner et al. propose a theory of conceptual change which can be achieved through the development of historical models. Students consider early models and evaluate them on the basis of their explanatory and predictive powers. Ultimately, the model experiences a discrepant event creating dissatisfaction with the model. The model is then refined or replaced by a new model. For example, in the HDCM unit students explain mixtures and compounds using Dalton's model of the atom. Then, they are confronted with the question, "What holds the atoms together?" Some early interesting historical ideas such as the shapes of atoms (Gallendi) are compared to the student's ideas and eventually lead to a consideration of electricity as a bonding force. Students typically paint the textbook picture of the solar system model with a positive nucleus and electrons flying around the outside, but they experience dissatisfaction with this idea when they are asked to explain what holds the positive nucleus together. Alternative models, such as Thomson's plum pudding model are examined for their explanatory powers and for observations discrepant to the model. In this way, the tentative nature of science is naturally revealed and the nature of the atom can be discussed. Models and analogies are also a central means to invent explanations and make predictions. Students are actively engaged in this type of model construction and evaluation. Initially, there are no wrong models, but we select models which grant us greater explanatory power and we continually challenge, modify, and sometimes completely replace our models in science.

Gobert and Buckley (2000) recently outlined the basic assumptions and underlying principles of research programs in model-based teaching and learning. They accept the position that people construct and reason with mental models, and that the evaluation of a model may lead the learner to reject or revise the model. Buckley describes model-based learning as a dynamic, recursive process that involves the formation, testing, and reinforcement, revision, or rejection of mental models. In her study, Buckley used various models of the heart as a means of developing an understanding of the circulatory system and as an avenue for the learner to generate and consider further inquiries. In lieu of a factual accounting of the relationship between the circulatory and digestive systems, students utilize a multimedia approach, based on an anatomical context, which provides open access, when needed, to relevant information.

Derek Hodson (1985) also advocates the use of models. He argues that as children begin to acquire more complex experiences they need to develop their personal theories into more complex structures and they may pass through several developmental stages. These stages include a tentative introduction of several models, a search for evidence, selection of the best model through discussion and criticism, and further elaboration of the model into a more sophisticated theory. In science instruction, students should be able to introduce their own experiences, make their own ideas explicit through writing and discussion, and explore, challenge, and devise tests for alternative viewpoints.

Final form science, today's textbook approach, does not permit the opportunity for the student to develop tentative models. In the HDCM unit, students consider their preconceptions in the light of some of the early conceptions of great scientists. These early ideas form an introduction of a tentative model which can be confronted by unsolved puzzles and discrepant events as the model is modified or replaced by more a plausible model. Further, it promotes a better understanding of the nature of science by encouraging students to challenge early models of science and, ultimately, their own conceptions. In this way, the historical development of models also enables instruction to follow Hodson's path to a more philosophically valid curriculum (Hodson, 1985).

Recent curricular efforts, like Project 2061 (AAAS, 1993) and the Pan-Canadian science frameworks (CMEC, 1997), suggest that the nature of science should play a prominent role in today's science curriculum. However, little or no context is provided for teachers to implement goals such as the "development of scientific theories and technologies over time" (Pan-Canadian, p. 26) in the science classroom. I am suggesting that the HDCM can provide a context for addressing these nature of science outcomes, explicitly, and in a pedagogically sound and motivating manner.

In senior years, students begin to move from a descriptive mode of science to a more explanatory mode through the use of scientific facts, laws, and theories. I have previously stated that science education continues to focus on a textbook-centered presentation of the finished form of science which views science as an established body of knowledge where the facts, laws, and theories of science require minimal justification. In spite of recent curricular efforts (Pan-Canadian science frameworks) to promote a more eclectic view of science and an understanding of the nature of science, few contexts exist where such a view may be practiced in the classroom. I am arguing that, in many cases, the historical development of conceptual models (HDCM) will provide such a context to meet many of the goals and outcomes of the Pan-Canadian view of the nature of science. Consequently, a research project was undertaken to develop, implement, and evaluate an HDCM unit of instruction.

Chapter V

Methodology

Purpose

The purpose of the research study was to assess students' understanding of the nature of science and how this understanding was influenced by instruction which integrated the historical development of the model of the atom within the curriculum outcomes for the Chemistry unit of the Manitoba Senior 2 Transition science course. The research also investigated student attitudes towards the inclusion of history of science in their science course and the role that students believe history of science may play in understanding theories and models in science. The research questions which guided the study were:

1. How does the historical development of conceptual models (in particular, the model of the atom) influence students' conceptions of the nature of science?

2. What specific aspects of the NOS are influenced by the integration of history of science in science instruction?

3. What are the students' attitudes towards the inclusion of the history of science in their learning of scientific models and theories?

Participants

Participants in the research were 74 senior 2 (grade 10) science students from four different classes in three different schools in the province of Manitoba. The first class (Group A, n = 20) were enrolled in a private non-secular school. The students came from various backgrounds, usually middle class and upwards on a socio-economic (SES) scale[111] and attended the school for religious reasons. The teacher, Mr. A[112]. was a dedicated, committed teacher of science with seven years of experience. The second and third classes (Group B, n = 33) were enrolled in an independent non-denominational school. The students generally came from upper-middle class to upper class backgrounds on a SES scale and most of the students would likely pursue university studies in the future. Their teacher, Mr. B. was a science major with three years teaching experience. The fourth class (Group C, n = 21) were enrolled in a large suburban high school. The students came from various backgrounds across a SES scale. Their teacher, Mr. C was a science major with 6 years of teaching experience and an active involvement in the professional development of teachers. Each teacher had previously taught the Senior 2 transitional science curriculum and the timeframe[113] for instruction was approximately the same for each class.

The Senior 2 science course is compulsory for all grade ten students in Manitoba,

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111 In this study SES was not measured formally and the description of the students' SES is an assessment derived from the researcher's experience. It is not intended as a formal comparison.

112 All names in the research are reported as pseudonyms

113 All four classes started the first of September, 2000. Two classes finished by November and two classes finished by December. The hours of instruction was approximately 35 hours for each class.

so the students in the study represented a wide spectrum of abilities and interest in science. All of the classes were taught in a combined classroom/lab environments with access to adequate equipment and supplies.

The Developed Curriculum (HDCM unit)

The historical development of the model of the atom was integrated into the chemistry outcomes of the Manitoba Science 20S transitional curriculum[114]. The chemistry knowledge outcomes as prescribed in the Manitoba curriculum documents are organized by the following topics:

2.1 Names of the Elements
2.2 Characteristic Properties
2.3 Development of the Atomic Theory
2.4 Early Periodic Table
2.5 Modern Periodic Table

3.1 Composition of Compounds
3.2 Ionic Compounds
3.3 Compounds with Polyatomic Ions
3.4 Covalent Compounds
3.5 Conserving Chemical Resources

The unit was designed by the researcher, called hereafter the HDCM unit, and integrated the historical development of the model of the atom from the time of the Greeks to present day theories with the content outcomes of the standard curriculum. The research unit contained all of the curriculum outcomes listed above but not necessarily in the

114 The curriculum was called transitional before it was aligned with the Pan-Canadian Science Frameworks, (CMEC, 1997).

given order[115]. The development of the HDCM unit was guided by Lederman's recommendation that instruction in NOS must be explicit. In other words, we must plan for, teach, and assess specific aspects of NOS. Given that the compulsory nature of the course meant a cross section of students, a differentiated approach to instructional strategies was used. Students were asked to keep a NOS journal, to make concept maps and word cycles, to brainstorm about models and how to test the models, and they were also asked to discuss and write about their ideas with their fellow students.

The HDCM unit included all of the traditional outcomes as described in the curriculum document. However, as these outcomes were developed, students followed a storyline of the development of the model of the atom from the Greeks to modern day ideas. Other aspects of NOS were also introduced with historical vignettes, and wherever possible, the ideas of models, laws, and theories are discussed, questioned and revisited[116]. For example, the course begins with students mapping out their ideas of the nature of science. A "black box" activity was used to explicitly introduce the terms observation, inference, models, laws, and theories and then students related these ideas to a historical vignette. A short story was told about Tycho Brahe and Johanne Kepler who were gazing at the early morning sky. Students were asked to consider what each astronomer "sees" and what each astronomer tells each other what they see. The ensuing discussions revealed that although Tycho's and Kepler's observations may be the same

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115 Although the outcomes are mandatory the delivery and sequence of the outcomes are decided by each individual teacher.

116 For a summary of the historical aspects of the unit see the table in Appendix A.

each astronomer infers either a geocentric or heliocentric universe. The terms facts, models, laws, and theories were then explicitly revisited in this context.

The historical development of the atomic model was introduced with the competing models of the Greeks concerning the discrete or continuous nature of matter. Students described and used the four elements of the Greeks to explain the composition of modern substances. Zosimos' experiment[117] with boiling water was used to introduce the transmutation of elements. The idea of a scientific model was evaluated for its' explanatory powers and re-assessed in light of discrepant events or inconsistencies of the model. Later on in the course, students revisited Zosimos' experiment in terms of Lavoisier's explanation using the law of conservation of mass.

The HDCM unit was intended to cover the content outcomes of the prescribed curriculum while maintaining a historical perspective throughout the unit. In a traditional approach students' lab skills are developed through inductive experimentation often laid out for the student as in a recipe. In the HDCM unit, a historical perspective was maintained by introducing lab skills to students as the skills the alchemists needed to pursue the philosopher's stone and transmute one element to another. After developing the skills of the alchemists (traditionally these skills are described in the curriculum as the characteristic properties of matter like boiling point, density, and so on) the students began to take matter apart to determine if it was discrete or continuous in nature and if transmutation was plausible. They first identified mixtures, then compounds, then

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117 Zosimos' found in an early experiment that when water was boiled it "decomposed" into the element air and earth (a white calyx was left behind in the boiling pan).

elements. Historical activities included exploring "a day in the life of an alchemist" where students researched alchemy and the beginnings of modern chemistry. The story of Hiero's crown was used to introduce the characteristic property of density. The researcher made small gold crowns (copper painted gold) and coins (steel washers painted gold) and the students were challenged to determine if the crown was real gold or not. In this exercise, students developed two solutions to the problem. Either they held the mass constant and compared volumes (by displacement of water) or they held volumes constant and compared masses. Later, the unit mass concept was revisited for the development of the periodic table.

Using the skills of the alchemists students found that they could separate mixtures, and decompose and synthesize compounds. Eventually, they were unable to break material apart any further and their chemical analysis concluded with the discovery of elements. Consequently, we must explicitly alter our thinking from an inductive mode to a deductive mode. That is, we first devise an explanatory model for the components of elements and then develop ways to test the model. The historical development of Lavoisier's ideas was used to again address the use of a model. The problem of combustion using the phlogiston model was questioned using hands-on lab activities. Some traditional activities were adapted to fit this context. For example, in one laboratory exercise, students decomposed sodium chlorate into sodium chloride and oxygen. They massed the materials before and after and explained their results in terms of a simplified phlogiston model of combustion. That is, phlogiston was given off and the mass of the original substance decreased. Following this exercise, students burned copper dust. Again, they massed the materials before and after and discovered that the mass of the original substance increased (copper oxide was produced). Students tried to explain their results in terms of a phlogiston model but concluded that the model was becoming complicated. Lavoisier's experiments with combustion and respiration were introduced and the role of oxygen in combustion became the new explanatory model.

Next, the atomic models of Dalton, Thomson, Rutherford, and Bohr, were introduced for their explanatory and predictive powers. Students were involved in many activities to use the model and devise tests for the models' explanatory and predictive powers. For example, students used Dalton's model to explain the Law of Constant and Multiple Proportions and then later they used the Bohr model to explain how elements combined to form compounds. A demonstration of Thomson's plum pudding model was constructed by placing strong neodymium magnets inside small wooden spheres. A large glass dish was wrapped with number 12 wire and filled with water. When the wires are connected to a 6 v battery a magnetic field is produced inside the dish. The wooden spheres are placed in the water, one at a time, and they form stable patterns. The water is intended to be an analogue to the positive charge of the atom and the wooden spheres, immersed in the water, are the negative charges (electrons). Students brainstormed to devise tests of this model. The suggestion to pass something through the "atom" acts as a stepping stone to Rutherford's gold foil experiment. The teachers, and their students, quite enjoyed this demonstration.

As the models were developed, discrepant events such as the problems of bonding and spectral lines were encountered and the students were encouraged to revisit each model for its' explanatory powers. The Bohr model was used to explain bonding and students drew typical diagrams to illustrate the formation of elements and compounds. Mendeleev's periodic table was introduced using the combining ratio's of hydrogen and fluorine with various elements. Students then organized the elements on cards according to these ratios to construct their own table to find a pattern which was periodic. Finally, the HDCM unit concluded with a consideration of the quantum model of the atom and modern theories, such as the string theory, which, interestingly, raises the same questions of the Greeks concerning the discrete or continuous nature of matter.

The HDCM unit was intended to require 30 hours of instructional time. Each teacher reported taking more time so that the unit averaged about 35 hours in time. The teachers were provided with a set of student frame notes (for each student), a corresponding set of completed frame notes for the teacher, and a matching set of overheads. In this way, a uniform treatment of the outcomes was achieved and few activities were omitted by the teachers.

Procedure

The HDCM course notes were distributed in the April 2000 to several Senior 2 science teachers so that perspective teachers for the research project could review the unit and approach their local administration to participate in the study. Four teachers volunteered to participate in the study, one withdrew before the unit began. Each of the teachers had taught the course previously according to the curriculum guidelines outlined in the Department of Educations documents. At the beginning of the fall term, before classes began, the teachers met with the researcher to review the course outline, the labs, activities, supplies, and the history of science context for the unit. The teachers were assured that they would make the final curricular decisions in their classrooms and that their instruction was not being evaluated. However, the teachers were asked to record any omissions (such as a lab) or activity that they did not follow. Additionally, suggestions were made for assessment of curricular outcomes (such as the use of the NOS journal) but teachers were given control over assessment in terms of determining their students' grades. Information was exchanged so that the teachers could easily contact the researcher to ask questions or discuss difficulties or misunderstandings with the unit. During their instruction the teachers asked questions and provided evaluations through personal contact, or more usually, email discussions.

On the first day of classes, the teachers performed normal administrative activities (books, attendance, etc) with their students and at the end of the class permission forms and information for parents were distributed (see Appendix B,C, and D for the forms). Students were informed that they would be asked to complete the VNOS test before and after the unit and that some of them would be asked for an interview. They were informed that participation was voluntary and their parents were informed of the nature of the study and the types of data to be collected (see the Appendix for details). Each student participant was required to have parental permission to participate in the study. Approximately, 85% of the parents granted permission for a total of 74 students. The next day the teacher collected the permission forms and students wrote the VNOS test before any instruction began. The permission forms and VNOS tests were picked up by the researcher and held until the end of the course (the analysis of the VNOS pre and post tests took place after the course was completed). To begin the unit, the student frame notes were distributed and the students made their NOS journals. The first class began with a concept map exercise to answer the question, "What is Science?"

During instruction, students periodically made entries in their NOS journal. At the end of the unit (approximately 3 months) the students wrote the VNOS test again and the NOS journals and VNOS post test were picked up by the researcher. In the next two weeks, the VNOS pre and post tests were reviewed by the researcher and a preliminary NOS profile was compiled for each student. From this profile and the student responses, 24 students (8 from each group) were selected to be interviewed. The selection process was intended to achieve a cross-section of student views including the students (n = 3) who expressed some concerns about the use of the history of science in the unit. In the month following the completion of their unit, these students were interviewed and the interviews were audio recorded for transcription. Finally, each teacher was asked to submit an evaluation of the unit and their experiences.

<u>The Instrument (VNOS-*Form B*)</u>

The VNOS (Lederman et al. 2001) is an open ended questionnaire designed to elicit students responses about the tentative, empirical, inferential, creative, and subjective aspects of NOS as well as the meaning and relationships between theories and laws. There are three version of the VNOS, form A, form B, and form C. Form B was used in this study.

The questions are:

1. After scientists have developed a theory (e.g., atomic theory, kinetic molecular theory, cell theory), does the theory ever change? If you believe that scientific theories do not change, explain why and defend your answer with examples. If you believe that theories do change: (a) Explain why. (b) Explain why we bother to teach and learn scientific theories. Defend your answer with examples.

2. Science textbooks often represent the atom as a central nucleus composed of positively charged particles (protons) and neutral particles (neutrons) with negatively charged particles (electrons) orbiting the nucleus. How certain are scientists about the structure of the atom? What specific evidence do you think scientists used to determine the structure of the atom?

3. Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.

4. How are science and art similar? How are they different?

5. Scientists perform experiments/investigations when trying to solve problems. Other than in the stage of planning and design, do scientists use their creativity and imagination in the process of performing these experiments/investigations? Please explain your answer and provide appropriate examples.

6 [118]. In the recent past, astronomers differed greatly in their predictions of the ultimate fate of the universe. Some astronomers believed that the universe is expanding while others believed that it is shrinking, still others believed that the universe is in a static state without any expansion or shrinkage. How were these different conclusions possible if the astronomers we all looking at the same experiments and data?

An additional question to probe students' ideas about the inclusion of the history of science was added to the VNOS post-test.

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[118] The VNOS-B was obtained, with permission, directly from its' author Norman Lederman in April 2000. The test was sent as a email attachment and included comments for the researcher after each question. Because of an error in photocopying the comments were included in the final VNOS question #6 and remained undetected before administration of the test. Consequently, question #6 was omitted from the analysis.

7. What role do you think the history of science may play helping you to understand scientific models and theories?

The Interview

The VNOS post test was followed by interviews to clarify student responses and provide students a further opportunity for feedback and input into their science education. After a preliminary analysis of the VNOS, twenty-four students, eight from each group, were selected to achieve a cross-section of students. Time constraints prohibited the interviewing of all students. However, Lederman et al. (2001), using the VNOS instrument, report that interviewing a sample of 15 - 20 % is adequate to gauge the meanings associated within a specific group. Lederman and O'Malley (1990) reported selecting and interviewing 20 of 69 participants in their study and they based their selection on the most highly verbal students who were representative of the different views of NOS and who had changed their views from the pre to post-test. In this study, a similar protocol was followed but since students attitudes towards the inclusion of HOS in their science course was also of interest, the very small number of students (n = 3) who expressed concern about HOS were automatically selected for interviews.

At the conclusion of the unit, a total of twenty-three students were interviewed with one student choosing not to participate. During the interview, the students were assured that there were no right or wrong responses to the VNOS and that the researcher was interested in their thoughts about the nature of science. The students were reminded of their responses to the open-ended questions and they were asked to explain and/or clarify certain aspects of their answers As the interview progressed, additional probing questions were asked by the researcher. Typical questions asked by the researcher included (sometimes in response to students ideas):

- What is the role of theories in science?
- What do we use our theories for?
- How will we know if we have the correct theory?
- What kinds of experiments did scientists perform to test their model of the atom?
- How do we prove a theory? a law?
- What do you mean by proof?
- What aspects of science are creative?
- What is an example of scientist who thinks about what would happen before she does an experiment?
- What are some things that might influence the views of a scientist? What led you to consider these influences?
- What led you to believe/change your response from the pre to the post-test?

The interviews lasted approximately 30 minutes each and were conducted in a familiar environment in the students' school. A suitable amount of wait-time was given students to respond and the researcher exercised caution with his prompts such that students were not led to some specific response. The interviews were audio taped and transcribed for analysis.

Validating the Students' Responses

Lederman et al. (2001) reported that the results of the interviews have supported the validity of the VNOS for a large number and broad range of respondents. In order to ensure that the students responses are interpreted as valid responses, a second researcher scored the VNOS results for the twenty four students selected to be interviewed. The results were compared with the first researcher and the percentage agreement for each question is reported in Table 6. A high degree of agreement was generally obtained. In cases of disagreement in the coding of the responses, the researchers met and used a consensus model with a low inference interpretation. In all cases, final agreement was achieved. The interviews of the 23 students were then compared with the pencil and paper responses to further clarify and validate the students answers.

Table 6: Agreement

Question	Percent Agreement
1	75
2	82
3	86
4	82
5	86

<u>Building a Students' NOS Profile</u>

An interpretation of any kind of student understanding of the nature of science must recognize that students may hold a number of different and sometimes conflicting ideas about certain aspects of NOS. What a theory is, or is not, or the complex relationship between observation and evidence are just a couple of examples of ideas which cannot be considered simplistic for a 15 year old beginning to think abstractly. Therefore, we must recognize that students may hold a spectrum of ideas in their understanding of NOS, some of which will be contradictory. As previously discussed, Likert type, and agree/disagree type tests, do not provide any insight into this continuum of ideas that students may hold about the nature of science.

The interpretation and analysis of the VNOS data in this study complies with the protocol outlined in Lederman et al. (2001). This analysis of the VNOS is not intended to provide a simple checklist of students' views of NOS. Certain questions target specific aspects of NOS and many of these aspects overlap between questions on the test. For example, a student may suggest in question #1 that they believe in the tentativeness of theories but in question #3 express a hierarchal development of theories into laws. In order to present a comprehensive picture of respondents' views, a profile for each student is developed. In this profile the students' answers to each question are summarized in a table (see table 7) and coded as:

(-) naive:	inappropriate or inconsistent response
(+) emerging	simple agreement or ideas which can act as a basis to develop more sophisticated ideas of NOS, Single positive (+) responses can still be considered naive but suggest that progress can be made by the student by strengthening or building on their ideas.
(++) more informed	adequate description/response, response is supported with evidence and/or examples.

Expert ideas, that is, a strong articulation of ideas about NOS supported by evidence and examples could be coded (+++). However, in consideration of the age of the learners, the goal of the unit is to move students towards a more informed view of NOS and not the expert's views. It is possible, and often happens, that students hold positive and negative ideas (+-) about NOS. Consequently, for each question, an interpretive framework is outlined with actual student responses as illustrative examples. Although student responses are not taken literally, a low inference model is followed such that student responses are not interpreted with high inference meanings unless substantiated by a follow-up interview. For a final analysis, a student profile is developed for each student (table 2 is a partial profile). For example:

Student1's response to question 1 on the pre-test:

> "Yes, I do think a theory can change. I believe this because I know that a law is what becomes of a theory after scientists have discussed and agreed that it works".

Student1's response to question 1 on the post test:

> "I believe theories can change because they are just a possible solution. We study these theories to see what people were thinking about while they were studying and so we see how far we've come. We had 4 models of the atom and we still haven't come up with a perfect one".

Table 7: Sample Student Profile

Student1 profile			
NOS Question	Initial	Final	Comments
1. Theories and tentativeness	-, theory becomes law	++, theories are a possible solution, can change, 4 models of the atom, HE	Student demonstrates positive change Uses historical examples. Does not address theory to law view in post-test.

Again, we use a low inference model with respect to interpreting change between the pre and post tests. As in Student1's profile, if a student claims that theories become laws in the pre-test , no assumption that this position changes can be made unless the student addresses the theory/law statement in the post-test.

One of the major advantages of the VNOS test and a tabular representation of data is reflected by the researchers ability to cross-reference student responses between questions. Indeed, this could prove useful for assessment and program planning by the classroom teacher concerning their students' understandings of NOS.

For the final analysis and comparison of pre and post test results, the codes are tabulated and histograms for each question are produced. As we interpret the findings we must remain cognizant of the meaning of the coding. The coding does not equate to a direct numerical order. The great advantage of this coding is that it reflects the fact that students can and do possess multiple ideas about the various aspects of NOS. However, we can only evaluate a student's change or progress based on what they have said, not on what they haven't said. For example, a student may possess a positive idea and a negative idea about theories simultaneously. Later, the student may only express the positive idea, perhaps strengthening their idea or making a positive change in their view. However, if they do not address the negative aspect of the original response we can make no assumptions about change with respect to this response. Therefore, it is difficult to assign any meaning to certain changes. For example, a change from +- response in the pretest to a + response in the post-test cannot be automatically be viewed as a positive change unless the student specifically addresses the initial negative response. In this case, an assessment of change can only be done by inspecting the individual responses to determine if there is a strengthening of ideas, a positive change in ideas, or no change at all. A graph cannot indicate this type of change. However, the graphs do provide some useful visual information with respect to the overall movement between the pre and post test results. This type of analysis is viewed as a positive improvement over previous Likert-type tests which "mask" students conflicting ideas or naive interpretations of the various aspects of NOS.

<u>Comparison of Pre/Post Tests</u>

Each of the individual responses on the pre/post tests were compared to determine if the student experienced no change, a positive change, or a strengthening of ideas. A positive change represents movement, along the spectrum of responses, to more informed ideas. That is, usually from "-" to "+", "++", or "++-" and from "+" to "++". Students strengthened their response when they did not significantly change their views but their views were more clearly articulated and/or strengthened by supportive arguments and examples. The use of supportive arguments was an important consequence of the research which emerged in the analysis of student responses and interviews. Lederman and O'Malley (1990) report that students generally fail to provide examples to support their claims. In their study, although students continued to maintain their positions in the interviews, they could not provide additional examples or support for their responses. The researchers concluded that "the inability of most students to identify the sources of their beliefs appears to indicate that an understanding of the nature of science is taught and learned implicitly" (p. 235). This research study partially corroborates this case as many students failed to adequately support their position or provide examples, especially in the pre-test. There may be several reasons for this type of response, or lack of response. The compulsory nature of the course means all students, including uninterested and unmotivated students, take the course. The age of the students (15 to 16 years old) is another possible reason for the students' failure to provide any more than a basic response. Some students seemed to show a reluctance to articulate what they know for fear of revealing what they don't know. Many students simply do not know how their ideas fit in with textbook science. In her interview, Rita describes how she was unaware how her picture of an atom fit in, even though she held a simplistic view.

> "like before we did our unit this year I wasn't sure if I was right or wrong thinking that it was a dot, but after I knew that I wasn't you know, completely out of the loop".

A comparison of the pre and post tests was also made to determine the influence of the historical perspective adopted in the unit. To what extent can we believe that the history of science integrated into the unit played a role in altering students' views of the nature of science? To help assess the role of the history of science each individual response on the VNOS was reviewed for the use of historical examples (HE) and supporting arguments to determine the influence of the history of science on students' ideas about NOS. In general, students cite examples and supporting arguments in three different ways. First, by just naming the example, secondly, they use the example as supporting evidence by commenting or expanding on the example. Or, thirdly, students use their examples inappropriately as misinformation or to support naive claims. For each question, the evidence, examples, and supporting arguments were assessed and recorded for the three categories (example only, supporting argument, and inappropriate use) and if they were historical examples. In this way we are able to determine if the historical aspects of the course influenced students' arguments.

Chapter VI

Results

Question #1 VNOS Interpretation and Analysis

After scientists have developed a theory (e.g., atomic theory, kinetic molecular theory, cell theory), does the theory ever change? If you believe that scientific theories do not change, explain why and defend your answer with examples. If you believe that theories do change: (a) Explain why. (b) Explain why we bother to teach and learn scientific theories. Defend your answer with examples.

Bell (2001) reports that more informed opinions of NOS believe theories can change. A variety of reasons are provided for this change including the emergence of new evidence or new insights, consistency with other theories, and social and cultural influences. Experts agree that good theories are well-supported by empirical evidence and provide a framework for current knowledge and future investigations. Expert views also distinguish between different classes of theories, from speculative to robust. Speculative theories are ideas which are put forth to explain natural phenomena for which no satisfactory explanation exists. Evidence for speculative theories can be weak, or non-existent, but the theory helps define a research program to begin to formulate predictions and tests of the theory. As evidence accumulates, theories move along a continuum of acceptance in the scientific community and ultimately become robust theories. Robust theories make solid predictions, have considerable support in terms of empirical evidence, and define productive research programs.

Student responses to this question illustrate the necessity for a careful analysis including interviews of students. Young people can, and do, say that theories change for a variety of reasons. Students are found to hold ideas about the definition, development, and origin of scientific theories, as well as, ideas about the status of evidence and the factors which influence theory choice. Students were found to demonstrate a spectrum of understanding about scientific theories ranging from naive, uninformed, or misinformed ideas to a more sophisticated, informed understanding.

The naive position in this spectrum is not based on philosophical preference. The view that theories are just opinions, or that theories are beliefs that can change because we can simply change our minds is seen as a naive position. Also, the naive realist view that represents theories as emerging from nature, that is, that they are "out there" waiting to be discovered is also considered naive. In this view, theories change until they become correct or they advance to law status when they are "proven". In the interpretation of the VNOS all of these naive views were scored with a (-).

Positive responses for question #1 can range from basic ideas which serve as starting points from which further understanding can build, to a more sophisticated understanding of the nature and development of theories. A student with a basic positive response (+) generally agrees that theories change and includes recognition of the empirical status of theories. This view generally holds that theories can change if they are proven incorrect by virtue of observation or the emergence of new evidence. These students often hold the view that as technology changes, our observations become more exact, or we see things we haven't seen before, and we can therefore make better theories. While this view recognizes the empirical nature of science the belief often remains that theories emerge from nature or that theories advance to law status when they are proved. In this case, it is not unusual for students to be coded (+-) to indicate that they hold both positive and naive ideas about theories simultaneously.

I also include as a basic positive response the notion of a theory as a guess (often described by students as an educated guess) or an idea. It is recognized that this view (educated guess) is still naive but it does provide a foundation (speculative theory) from which we can construct a more sophisticated understanding. This notion advances beyond the view that theories emerge from or are discovered in natural phenomena to consider that theories are ideas about nature formulated by the human mind. However, the student often fails to address or recognize that we look to nature for evidence to support our ideas and it is again not unusual to find students who score both positive and negative in this respect.

Students who are able to recognize a basic idea in more than one category (definition, origin, etc) are represented as more informed. The more informed respondent's view represents theories as ideas which can be supported by evidence and observation. These students often suggest that new insights or evidence can lead to better ideas (++). Theories as explanations (++) is seen as a more powerful statement than "to understand how things work" (+). The more sophisticated view outlines theories as explanatory systems of natural phenomena. When a student begins to consider theories as explanations of natural phenomena, we can begin to build the expert's understanding of the nature of science who view theories as explanatory systems for natural phenomena and that theories can range from speculative to robust.

Each student's response is graded according to this continuum of ideas from "-" to "++" such that "-" represents a more naive response and "+" represents a more informed response and level of sophistication. A tremendous advantage of scoring this way is that students can, and do, hold conflicting ideas about theories. For example, a student may see theories as explanations of natural phenomena (++ response) but continue to believe that some theories have been proven correct and can never change (- response). Table 8 summarizes some results from question 1 of the VNOS and includes illustrative examples of actual student responses.

Table 8: Question #1 Illustrative Examples

Symbol	Comments:Q1	Illustrative Example
-	inconsistent answer or naive responses which include: theories never change, theories are just beliefs/opinions, theories can change until they are correct, or theories change into laws when they are proven.	"Some theories, like with atoms, do not change because it will always be a proton, neutron, and electron".
+	affirmative response with basic explanation such as: they've always changed, if we discover new information, as society and technology changes, to understand how stuff works, theory is an idea.	"I think that theories can change because you might make a theory and then discover some new info that will make your theory change". "I think that theories can change, because the word "theory" means an idea that someone had".
++	Theories are ideas which are supported with evidence/examples, we can have new ideas, or refine an old one. Theories are explanations	"I believe that theories do change because a theory isn't a fact, it's an idea that tries to explain how something works".

Data Analysis Question Number One

Based on coding

Table 9

Pre Test				
-	+-	+	++-	++
13	16	26	11	8
1	2	3	4	5
Group				

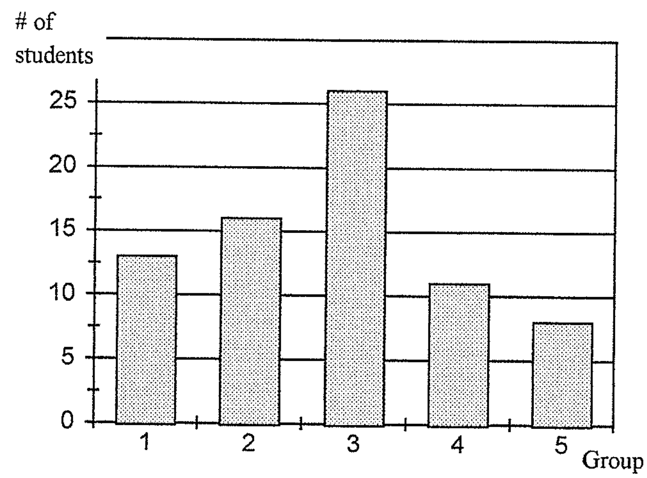

Figure 10

Table 10

Post Test				
-	+-	+	++-	++
4	9	32	6	23
1	2	3	4	5
Group				

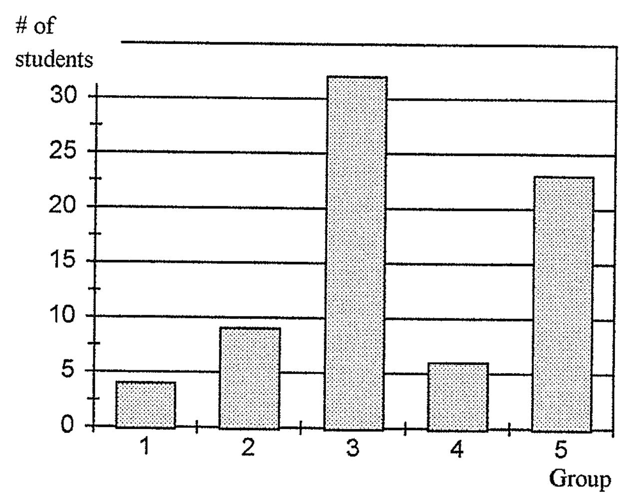

Figure 11

While it is difficult to assess the meaning of a change from -+ to + without examining the actual response, the graphs do give a visual representation of a general movement towards a more informed view after instruction. Regardless of the status of the negative responses which may not have been addressed, we view this as a positive result. Before instruction, 26% of the students (19) held more informed views (++- or ++) while after instruction 39% (29) held more informed views. Additionally, 18% of students (13) initially held only negative views while post instruction only 5% of the students (4) held only negative views.

After coding, each students' post-test response was compared to their pretest result. If a student advanced from a (-) to a (+), (++), or (++-) or from (+) to (++) they were determined to have made a positive change in their understanding. Responses were also carefully examined to determine if the students' position was strengthening by articulating their views more clearly and/or by providing better arguments to support their views. Because many different views about theories can be held each students' response must be carefully examined to make sure that the student addresses their initial views. If a student did not specifically address initial views no assumptions were made.

Table 11 shows that a total of 41 students (55.4%) strengthened or positively changed their views about the nature of scientific theories in question #1.

Table 11: Question #1 (All Students)

n = 74		
Strengthen View	Positive Change	No Change
24	17	33
32.4 %	23.0%	44.6%

However, it is important to note that 19 students initially held more informed views of NOS ("++" or "++-", table x). Therefore, the number of students who entered the course with less informed ideas was, 74 - 19 = 55. Of the 19 students with more informed ideas, five were determined to have strengthened their ideas in the VNOS post-test. Consequently, we can adjust the data to consider only less informed students. Table 12 shows that 65.4% of the students who entered the course with less than informed views of NOS strengthened or changed their views positively.

Table 12: Question #1 (Only students who initially held less informed views)

n = 55		
Strengthen View	Positive Change	No Change
20	17	18
34.5%	30.9%	32.7%

The Role of History of Science (Question #1)

To what extent can we believe that the history of science integrated into the unit played a role in altering students' views of the nature of science? In question #1 students were asked to explain their answers and provide examples. Table 13 summarizes the examples that students provided to support and help explain their answers on the pre and post VNOS.

Table 13

Example	Pre	Post
No Example cited	43	32
Atomic Theory	7	8
Cell Theory	4	2
Kinetic Molecular Theory	4	1
Gravity	3	0
Atomic Model	4	20
Flat Earth	7	2
Helio/Geo Universe	2	1
Conservation of mass	0	1
Phlogiston	0	8
Fossil Record	1	1
Relativity	1	0
Heat	1	0
Periodic Table	0	4
Total	34	48

Note: Some students cited more than one example.

A total of 34 examples were cited by students in the VNOS pre test but it should be noted that 15 students cited the examples (Cell, KMT, and Atomic theories) which were already mentioned in the wording of the question. Interestingly, in the post instruction test, fewer students (only 3 students compared to 8) choose to use these examples (cell theory or KMT) as an example or supporting argument). Additionally, many naive examples, such as the "flat earth theory" (n = 7) and the "theory of gravity" (n = 3) were cited. In the VNOS post-test, 48 examples were cited by students in their response for an increase of 41% in the total number of examples cited. Further, even though the references to the Cell theory and KMT remained in the question itself, most students began to rely on the historical references, such as the atomic model and phlogiston, found in their instruction. The table also shows that the number of students who did not cite an example in their answer decreased from 43 to 32, a decrease of 26%.

More importantly, we must examine how students use these examples in their responses. We find that students generally use these references in three different ways. First, as an example only, by simply naming the example, that is, "the cell theory". The reference is not used in any way to defend the respondent's position. The second way that the reference is used is as part of a supporting argument or as evidence or reason to believe. In this preferred use, the reference is used appropriately, and in context. For example, a student who reports that, "The atomic theory has changed greatly from the ancient Greek ideas about the four elements to modern knowledge of sub-atomic particles and quarks" is considered to be stronger that the students who simply cites "atomic theory" as an example. Additionally, strong supporting arguments reflect "reasons to believe" and make connections to the nature of science. In her interview, Lana discusses how the historical perspective influenced her thinking:

> "Well, I guess it was when we went through all the different methods, like all the different theories that they had about the atom and the electrons and protons and where they were placed and stuff. It showed that it always, that it had always changed and it would keep changing because there was no way they could find a true model for it. And, from the way Mr. A. talked, led me to believe that all theories were like that"

The third way a student uses a reference is inappropriate, that is, it is used incorrectly, or as supporting a naive argument. One student claimed that , "After a theory has been developed it does not change. For example, cell theory will never change. The way the human body works will never be altered".

Table 14 shows how students used their references in the pre and post instruction responses to question #1.

Table 14

	Example Only	Supporting Argument	Inappropriate Use	No example cited
Pre	9	14	11	43
Post	8	38	2	32

Note: the number does not add to 74 because some students cited two examples.

The data indicates a rather significant shift in the use of supporting arguments from the VNOS pre to post tests, with more than double the number of references used as supporting arguments in the post test and a significant drop in the number of inappropriate uses.

Table 15 shows the breakdown of students who strengthened or positively changed their views and who explicitly used historical references (HE) to support their answers.

Table 15

n = 74			
Strengthen (HE)	Positive Change (HE)	Strengthen (no HE)	Positive Change (no HE)
19	10	5	7
25%	14%	7%	9%

Thirty nine percent (39%) of all students (29/74) strengthened or positively changed their views on the nature of scientific theories using historical references from the unit in their responses to question one of the VNOS. Again, considering that 19 students held more informed views of the nature of theories we can adjust the data for students who held less informed views only. Five of the 19 students with more informed ideas strengthened their views and all used historical references. Table 16 illustrates the data for students who initially held less informed views of NOS.

Table 16

n = 55, Students who initially held less informed views			
Strengthen (HE)	Positive Change (HE)	Strengthen (no HE)	Positive Change (no HE)
14	10	5	7
25.5%	18.1%	9.0%	12.7%

The data in Table 16 indicates that forty-four percent (44%) of students (24/55) who initially held less informed views, strengthened or positively changed their views using historical references to support their responses.

Summary Question One

There is an overall shift in students' understanding of NOS aspects of theories towards more informed ideas. The majority of students (55%) in the study strengthened or positively changed their views about the nature of scientific theories. It should be noted that the goal of the HDCM unit was to achieve a more informed understanding of NOS and it was not the intention of the unit to expect students to achieve an experts understanding of NOS. Consequently, we would not expect students with initial informed ideas to make significant gains in their understanding. When we adjust our data to reflect only those students who entered the course with less than an informed understanding, we find that a significant majority (65%) strengthened or positively changed their ideas. This result is very encouraging and the manner in which students employed their examples in the post-test strongly indicates that the historical content of the unit accounts for this change. Moreover, there are reasons to believe that many of the students who did not include historical references in their responses were influenced by the historical content of the unit. In the interviews, some students who did not include historical examples in their written VNOS responses used them in the interview to support their answers. For example, in the pretest Val said that she didn't think that theories changed and in the post-test she responded that "theories change, that is why they are called theories". In her written response no specific historical reference was made by Eva. However in the interview which was held a month later she was questioned for the source of her change:

> I: What led you to change your ideas from I don't think theories change to theories do change,
>
> Val: "I guess the explanations of the other theories that we had like Dalton's model and all that stuff .. the fact that there has been so many theories and models that have been maybe published or shown during class and they just said no this isn't probable anymore".

Further, many students who made no reference to historical examples in question #1 reflected an understanding of the historical nature of the course in other questions. For example, in question #1 Aaron made a positive change in his ideas about theories and tentativeness during instruction. However, in his written response to question #1, Aaron did not articulate any reason for this change. Additionally, Aaron did not cite historical references in the interview when he was asked for his response to question #1. However, in his interview response to question #2, Aaron mentioned the "most recent model" of the atom and when he was questioned about scientists' certainty Aaron responded:

> "Well, in the course we learned how it started with one theory and it kept on changing like even though it seemed like this had to be true during the experiments it turned out it wasn't true. So the idea that it kept on changing made me think they maybe don't really know for sure".

Although Aaron was unable to cite the names of the actual models he studied it is clear that he understood that models changed from a historical perspective. It also seems clear that this understanding of the changing nature of theories was the basis for his change in question #1. While we have no way of knowing how many students (without interviewing all of the students) neglected to include HOS references in their written work, we can conclude that the percentage of students who were influenced by HOS is actually higher than the data indicates. Additionally, the student profiles indicates that many students used HOS references in their responses to other questions suggesting an overall influence of HOS the majority of students.

These results must be viewed as significant in establishing that the historical perspective was influential in enhancing student attitudes about the nature of scientific theories.

VNOS Question #2 Interpretation and Analysis

Science textbooks often represent the atom as a central nucleus composed of positively charged particles (protons) and neutral particles (neutrons) with negatively charged particles (electrons) orbiting the nucleus. How certain are scientists about the structure of the atom? What specific evidence do you think scientists used to determine the structure of the atom?

Bell (2001) reports that experts' views about theoretical entities in science reflect an understanding of the inferential nature of scientific models. In their responses, the expert group used qualified language (a healthy skepticism) to describe scientists' certainty and the experts recognized a role for indirect evidence and/or inference in atomic models.

In their answers to VNOS question #2, students addressed the certainty that scientists have about the model of the atom and the type of evidence scientists use to believe in the structure of the atom. Students held varying opinions on the structure of the atom but often did not supply reasons to believe in the structure or they just deferred to authorities, like the textbook or the scientist for evidence of the structure of the atom. Naive responses graded negative (-) suggested that scientists are very sure or certain of the structure of the atom and/or that scientists used direct observation (such as a microscope) as their evidence. Other naive negative views represented the atom as an exact copy or replica of reality or the student simply deferred to the authority of the scientist or the textbook..

Positive responses which demonstrate emerging (+) ideas include that scientists are not certain about the structure of the atom and/or that the evidence they use is more indirect. We also rate positive an answer that suggests a healthy skepticism. That is, that scientists have a good idea about the structure of the atom but that they remain uncertain about certain aspects of this structure. Commonly, positive responses for the evidence that scientists use are references to experiment's like Rutherford's gold foil experiment or to the behaviour of elements in reactions. More informed views (++) express both positive ideas about scientists' certainty and the use of indirect evidence. Table 17 highlights some student responses with illustrative examples.

Table 17

Symbol	Comments:Q1	Illustrative Example
-	inconsistent answer, naive responses include: scientists are very sure or certain of the structure of the atom, evidence is by direct observation (usually by microscope), the atom is an exact copy reality, a deference to authority.	"the scientists are very sure of how an atom is structured because they have seen it like that in powerful microscopes". "they must have some really good proof for it to be shown the way it is in textbooks"
+	Scientists are not very sure about the structure of the atom, the evidence is more indirect, the model may change in the future.	"They aren't certain because they can't see it, so they can't tell what it looks like" "Rutherford's experiment, when passing through the atom you hit something hard which directs it"
++	More informed views (++) express both positive ideas about scientists' certainty and indirect evidence.	"scientists are never sure, by experimenting they get a general view. ex. one scientist shot electric waves through an atom, some did not go through, so they discovered the nucleus"

Data Analysis Question Number Two

Based on coding

Table 18

Pre Test				
-	+-	+	++-	++
49	15	8	0	2
1	2	3	4	5
Group				

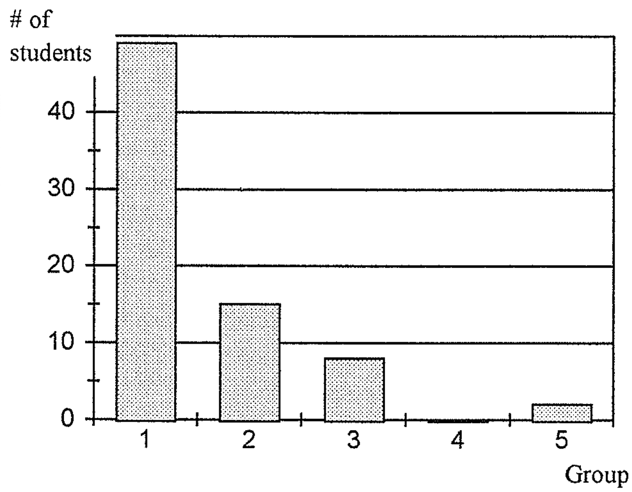

Figure 12

Table 19

Post Test				
-	+-	+	++-	++
19	15	26	1	13
1	2	3	4	5
Group				

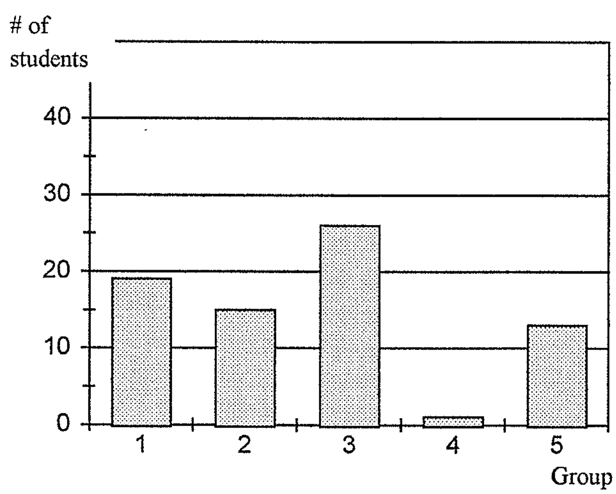

Figure 13

While it is difficult to assess the meaning of a change from -+ to + without examining the student's actual response, the graphs do give a visual representation of a significant reduction of the naive view and a general movement towards a more informed view. Part of the reduction of the naive view concerns the number of students who cite the microscope as evidence of the atom. In the VNOS post test, far fewer students relied on the microscope as evidence for the structure of the atom. While many of the students did not address the microscope in the post test, and we have noted that we cannot make judgements about change in the students views unless they address those views, the interviews revealed that many students now believed that you cannot see the atom. However, the interviews also revealed that some students believed that high technology microscopes could "get you closer" to the picture of the atom. Indeed, in recent years, high technology microscopes have brought us closer to the atom but there is no indication that students were aware of any connection to their school science.

Before instruction, 3% (2 of 74) of students held more informed views while after instruction 19% (14 of 74) held more informed views. Additionally, 66% of students (49/74) initially held only negative views while post instruction only 26% of the students (19/74) held only negative views.

Table 20

n = 74 models		
Strengthen View	Positive Change	No Change
18	24	32
24.3%	32.4%	43.2%

Table 20 shows that 57% (42/74) of the students strengthened or changed their views positively. Unlike question #1, only 2 students initially held more informed views of NOS. Therefore, no adjustment for students with less informed views was undertaken.

The Role of History of Science

To what extent can we believe that the history of science aspect of the course plays a role in altering students' views of the nature of science with respect to the structure of the atom? In question #2, students were asked "what specific evidence do scientists have for the structure of the atom?" Table 21 summarizes the nine (9) different responses students provided for evidence of the structure of the atom.

Table 21

	Evidence Cited	Pre	Post
1	Don't know, no evidence cited	20	21
2	Microscopes	23	9
3	Parts, features of the atom, as depicted in a picture or diagram	13	13
4	Authority, textbooks, scientist	4	3
5	High Tech	5	3
6	Energy	3	0
7	Unspecified experiments, data	7	15
8	Rutherford gold foil exp	0	13
9	Reactivity, how elements combine	2	4

In their study, Lederman and O'Malley reported that many students do not provide any evidence or reasons to believe, even when they are asked. This study supports that finding. In the pre-test 20/74 (27%) and in the post-test 21/74 (28%) of the students provided no evidence for the existence of atoms. Further, examples 2,3,4,5, and

6 from table 21 were all considered to be naive responses with little change before and after instruction.

Students who reported that scientists use experiments to test their models increased from 9.5% in the pretest to 20.2% in the post-test (pre = 7/74, post = 15/74). A more informed response indicates that indirect evidence is used and specific examples that can be used to support the model of the atom include the reactivity of matter and Rutherford's gold foil experiment. In the VNOS pre test, only 2 students (2.7 %) provided adequate evidence for the atomic model, both students cited reactivity of matter or how elements combine. In the VNOS post test, 4 students (5.4 %) cited reactivity of matter or how elements combine while 13 (17.6 %) cited Rutherford's gold foil experiment as evidence for the structure of the atom.

Table 22 shows how students used references to reactivity and table 23 shows how students used references to Rutherford's experiment in the pre and post instruction tests.

Table 22

Reactivity	Example Only	Supporting Argument	Inappropriate Use
Pre	2	0	0
Post	4	0	0

Table 23

Rutherford's Experiment	Example Only	Supporting Argument	Inappropriate Use
Pre	0	0	0
Post	8	5	0
Interview		5	

The interviews revealed that 22% (5/23) of the students in the interviews used Rutherford's experiment as a supporting argument even though they never mentioned the experiment in their written responses. This further supports the claim that the number of students who were capable of using historical examples as supporting arguments is much greater than the data indicates.

Finally, for question two, each students' pre-test response was compared to their post test result. If a student advanced from a (-) to a (+), (++), or (++-) or from (+) to (++) they were determined to have made a positive change in their understanding. Other changes were carefully examined to determine if the student's position was strengthening by articulating their views more clearly and providing better arguments to support their views if they had made positive changes.

Table 24 shows the breakdown of students who strengthened or positively changed their views and who explicitly used historical references to support their answers.

Table 24

n = 74			
Strengthen (HE)	Positive Change (HE)	Strengthen (no HE)	Positive Change (no HE)
11	16	7	8
14.9%	21.6%	9.5%	10.8%

Overall, forty-two (57%) students strengthened or made positive changes. In their responses to question #2, 36.5 % (27/74) of all students strengthened or positively changed their views on the nature of scientific models of the atom using historical references from the unit. Additionally, in the interviews, five more students used Rutherford's experiment as a supporting argument. Three of these students made positive changes and two strengthened their ideas of models. Therefore, if we adjust the data to include these students we have 43% (32/74) of the students strengthened or positively changed their views on the nature of scientific models using historical references.

Summary of Question #2

There is an overall shift in students' understanding of NOS aspects of the structure of the atom towards more informed ideas. The majority of students (57%) in the study strengthened or positively changed their views about the nature of the atom. A significant number (43 %) used historical examples to support their responses. Moreover, it was found in the interviews that a number of students who did not reference historical examples in their written work used them as supporting arguments in their interview. Thus, we may conclude that many of the students who did not use historical references in their responses were still influenced by the historical content of the unit. We must remember that there were 51 students who were not interviewed. While it is pure speculation how many of these students might have used historical references in their interviews we can conclude that the data represents the minimum influence of the HDCM unit and that the actual percentages would be higher.

Many more students held naive ideas about the structure of the atom than about the nature of scientific theories examined in question #1. The fact that many held on to these ideas indicates just how tenacious some of these misconceptions (i.e. we can see the atom through microscopes) can be. We should also note that even though students had previously studied the structure of the atom in junior high, it seems that is exactly what they studied, just the structure without any reason to believe in the nature of that structure. In other words, final form, textbook science which provided the student only with a diagram of the Bohr model.

It is noteworthy that multimedia sources such as Encarta and television were also cited. In an interview Lisa describes the source of her idea about the atom.

> I: Where did you get this idea?
>
> Lisa: Probably TV, from like those science cartoons, like Binky the Brain and stuff like that.

However, there are no indications that modern technology such as computers or animations were used in a way to present anything but the standard picture of the atom with no reasons to believe in its' structure.

Features of the atom cited by students were generally related to the diagram of the Bohr model of the atom. Many students used these diagrams as their evidence saying "how electrons move", "the electron shells", "how protons and electrons react, one going one way, one going the other". Most of these references refer to the Bohr diagram of the atom found in most textbooks and the way we use this picture to describe how elements combine. Of course, this is not evidence at all but a prediction of the model which needs to be tested through the understanding of mixtures, elements, and compounds. In the unit, this was approached from a historical perspective using the combinations of various elements with hydrogen and fluorine. However, because the teachers experienced difficulties with time the discussion necessary to support the model of the atom was quickly passed over in favour of the diagrams of the Bohr model. Therefore, the evidence to many students, becomes these diagrams, and for many (13 post-test) it appeared to stay that way. We might suggest, that it would be far more beneficial for students to develop their ideas about the existence and evidence of atoms from a historical perspective and eliminate altogether Bohr models and dot diagrams until a later course in chemistry.

On a more positive note, the historical development of the model of the atom provided students with opportunities to consider historical ideas and experiments as we collect evidence to support our models and confront evidence which is discrepant to the model. Students were actively engaged in the construction of Dalton's model of the atom to explain mixtures, elements and compounds. Later, they were confronted with the problem of the electrical nature of the Dalton model. A historical demonstration was developed to illustrate Thompson's model of the atom. Using this model students were encouraged to devise tests of the model. Ultimately, the idea surfaces to pass something through the model (atom). These brainstorming sessions gave students an opportunity to be creative and provided the teacher with a context to introduce Rutherford's experiment. At this level students cannot do Rutherford's experiment, but within the context of the historical development of the atom and their own ideas, the experiment makes sense. Many students in question #2, and other responses cited Rutherford's experiment as a good reason to believe in the structure of the atom. Often the students did not remember Rutherford's name but the essential details of the experiment made a great deal of sense with their prior knowledge of electrical charge. In her interview, Lana describes "the example of the gold foil".

> Lana: Well, he shot the alpha particles at the gold foil and they all deflected, some came back and some went through, some bent, and like, he thought that meant since the alpha particles were positively charged, if they hit the centre they reflected back because they were repelled.

In this light, as we begin to build reasons to believe we also begin to build a research program to answer more questions and search for more evidence. Students were encouraged to challenge and confront models in the same manner as the original investigations.

As previously discussed, the interviews revealed that some students who did not use historical references in their responses were still influenced by the historical content of the unit. In her written response to question #2 on the post-test, Teresa stated that scientists used tests like static positive and negative charges as evidence for the structure of the atom. However, in the interview, Teresa was asked:

I: So when you first started the course what picture did you have of the atom?

Teresa: Well, a little bit like, uh, the nucleus in the center.

I: And where did you get this picture?

Teresa: Um, we did that last year.

I: And you thought at that time that they used a magnifier[119] to see that picture?

Teresa: Yea.

I: Have you changed your mind on that at all?

Teresa: Yea, because they don't actually see the atom, it's what they believe it is.

I: What kind of evidence do scientists have that leads them to believe that?

Teresa: They do tests.

I: Do you know any other tests besides the one you gave?

Teresa: Well, there is the one where they found the nucleus and they like shot, uh, through it.

I: All right, And what did that tell them?

---

[119] The interviewer is making reference to the students' written response on the table in front of them.

Teresa: That there was something hard in the center of the atom.

In this case it may be that because Teresa had difficulty accurately describing Rutherford's experiment that she failed to include this as part of her written response. However, it is clear that she has moved from a very naive view of the structure of the atom determined by directly viewing it to a much more informed view that the atom is what scientists believe because of indirect evidence.

The interviews also revealed that some students acquired a much greater understanding than they revealed in their written responses. In his written response, Eric cited protons, neutrons, and electrons as evidence for the atom. In most cases, this type of response is given by students who are describing diagrams or pictures of the atom. However, in Eric's case the interview uncovers the real story.

I: Can you tell me what you mean by this sentence, "I believe scientists base these models on the evidence of protons and neutrons and electrons".

Eric: Well, like I guess like that one guy who shot the tin foil thing through the whatever, I guess that would be evidence.

I: Rutherford's experiments?

Eric: Yea.

I: When Rutherford fired the particles through the gold foil what did he measure or what did he observe as the result of that experiment?

Eric: Ah, wasn't it like the positively charged particles around the outside, are like scattered cause they hit the centre where all the protons would be.

I: Did he see the centre?

Eric: No. But he saw the results of it though.

I: So how did he come up with the idea there was

(interrupting)
Eric Well, cause like they went to the centre and deflected, that would mean the positives repel, similarly charged particles repel each other so the positively charged alpha particle would repel other protons, so I guess he decided that the protons were in the centre.

Finally, we may conclude that the HDCM unit is a successful approach to developing students' idea about the nature of scientific models. In general, students began to understand the nature of models and the kinds of experiments and indirect evidence that scientists use to evaluate their models. In particular, Rutherford's experiment seemed to provide students with a plausible explanation for the basic structure of the atom.

VNOS Question #3 Interpretation and Analysis

Is there a difference between a scientific theory and a scientific law?

Give an example to illustrate your answer.

Very few (if any) students recognize that theories and laws are different kinds of understanding. The more informed view describes a law as a relationship or pattern, often mathematical which may be constrained by several factors. For example, density equals mass divided by volume for constant temperature and pressure. Indeed, many laws, like Ohm's law or Newton's 2nd law, are used to define categories of materials (ohmic materials) or situations (inertial frame) which obey the law.

Expert views also distinguish between different classes of theories, from speculative to robust. Speculative theories are ideas which are put forth to explain natural phenomena for which no satisfactory explanation exists. Evidence for speculative theories can be weak, or non-existent, but the theory helps define a research program to begin to formulate predictions and tests of the theory. As evidence accumulates, theories move along a continuum of acceptance in the scientific community and ultimately become robust theories. Robust theories make solid predictions, have considerable support in terms of empirical evidence, and define productive research programs.

Naive views about the relationship between laws and theories are extremely prevalent among students. Generally, students hold that theories are either speculative or partially accepted.. Robust theories do not seem to exist in their understanding. Students often believe that if a theory has solid evidence, it is considered to be "proven" and becomes a law. This type of either/or response, that is, theories are not proven and laws are proven, reflects a belief in the hierarchy of theories progressing to laws and is considered to be negative (-) response on the evaluation of the question.

More positive responses suggest that we do have proof or evidence, or reasons to believe our theories and that laws are descriptions of nature used to "figure things out". Students who provide appropriate examples in context such as a pattern in nature, as in "what goes up must come down," are also seen to be more positive. Sometimes students see a theory as being associated with an individual in terms of a thought or idea and law as a collective agreement Students often have conflicting ideas about theories and laws and it was difficult to interpret many statements that they made such as "a law is a proven fact," especially when it stands alone without explanation. In these cases we graded the response neutral (+-).

The most informed views represent theory and law as different types of knowledge. Laws are described as relationships, a description or pattern in nature, and theories are represented as explanatory systems. Table 25 highlights some student responses with illustrative examples.

Table 25

Symbol	Comments:Q1	Illustrative Example
-	inconsistent answer, naive responses include: either/or situation, law is proven and theory not proven, law is fixed and theory is not, proven theory becomes a law, theories have no proof	"Yes a theory is before something becomes a law" "A scientific theory can't be proven but a law is proven".
+	Student recognizes that: theories are ideas that can have supporting evidence (i.e. theories are more than just speculation), laws are recognized as different than a theory, a rule or description in nature	"scientific theory, although there is much evidence, can't be proven". "law always happens and is consistent"
++	Theory and law are represented as different types of knowledge, there is no hierarchal relationship between law and theory, law is relationship, a description or pattern in nature, theory is an explanation of laws.	"A theory is just what someone thinks is the answer, they can't prove it, but it explains things". "theories support laws and can change"

Data Analysis Question Number Three

Based on coding

Table 26

Initial				
-	+-	+	++-	++
32	25	11	1	1
1	2	3	4	5
Group				

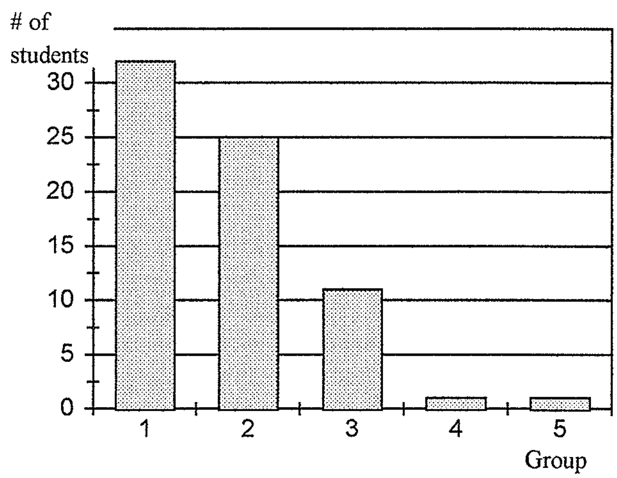

Figure 14

Table 27

Final				
-	+-	+	++-	++
14	35	22	2	1
1	2	3	4	5
Group				

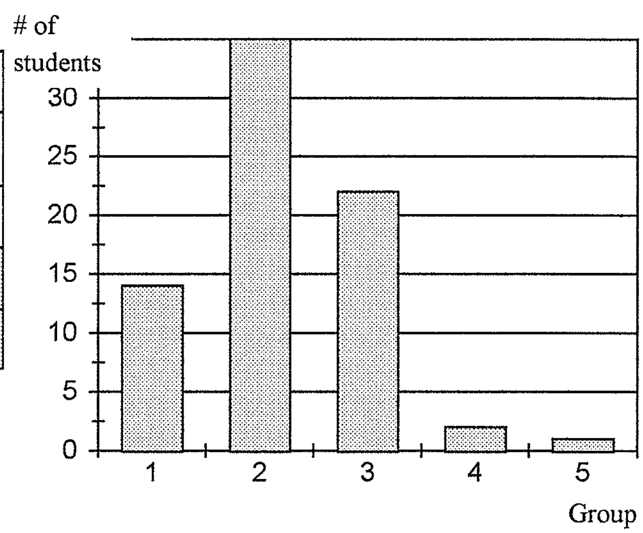

Figure 15

Unlike questions #1 and #2, we do not find a general movement towards a more informed view and only one student was identified as moving to a more informed view. The hierarchal nature of theory and laws was initially held by many students (57 coded either (-) or (+-)) and few students changed their view or addressed this perceived relationship in the post-test (49 coded (-) or (+-)). Students who moved from a (-) rating to a (+-) rating generally improved their view of the nature of theories, which is also supported by the positive results in question #1 but there were few changes in their understanding of the relationship between theories and laws..

Before instruction, 3% (2 of 74) of students held more informed views while after instruction 4% (3 of 74) held more informed views. Additionally, 43 % of students (32/74) initially held only negative views while post instruction only 19 % of the students (14/74) held only negative views. However, we caution about reading anything positive into this as students generally did not address the theory/law relationship but only improved slightly their views on the nature of theories alone.

Table 28 shows that a total of 32 students (43 %) strengthened or changed their views positively. Unlike question #1, only 2 students initially held more informed views of NOS. Therefore, no adjustment for students with less informed views was undertaken.

Table 28

n = 74 models		
Strengthen View	Positive Change	No Change
15	17	42
20.2 %	23.0 %	56.8 %

The Role of History of Science

To what extent can we believe that the history of science aspect of the course plays a role in altering students' views of the nature of science with respect to the relationship between theories and laws? For question three, each student's pre-test response was compared to his/her post test result. If a student advanced from a (-) to a (+), (++), or (++-) or from (+) to (++) they were determined to have made a positive change in their understanding. Other changes were carefully examined to determine if the student's position was strengthening by articulating their views more clearly and providing better arguments to support their views if they had made positive changes. Table 29 shows the breakdown of students who strengthened or positively changed their views and who explicitly used historical references to support their answers.

Table 29

n = 74			
Strengthen (HE)	Positive Change (HE)	Strengthen (no HE)	Positive Change (no HE)
11	7	4	10
14.9 %	9.5 %	5.4 %	13.5 %

24 % (18/74) of all students strengthened or positively changed their views on the nature of scientific theories using historical references from the unit in their responses to question three of the VNOS. Similar to the previous questions some students (n = 2) gave historical references in the interviews while they didn't cite the references in the written response. One of these students strengthened their position and the other did not

change. Again, this lead us to conclude that the data reflects a minimum percentage of students who use historical references.

Students generally did not use their examples to support the relationship between theories and laws, and in fact, they only expected from the wording of the question to includes examples. Therefore, it is very difficult to assign a specific role to HOS examples in terms of supporting the responses to question #3.

Summary of Question #3

There is an overall shift in students' understanding of NOS relationship between theory and laws towards positive ideas about theories and laws. However, students generally increased their understanding of theories or laws independent of each other and failed to make little or no movement on the relationship between theories and laws. While the relationship between theories and laws was dealt with explicitly by defining a law and a theory and examining them in context (for example, Lavoisier and the conservation of mass) it does not appear to be enough to overcome this tenacious misconception. It was not unusual to hear responses like Rita's or Lisa's.

Rita: Well they are basically the same thing, it's just that a law has been widely accepted and a theory is just an idea that somebody has in their mind but they haven't yet proved it.

Lisa: Um, a theory is just a law that's not proven yet. It's just not a defined law, it's still a law that's kind of foggy.

I do not believe that we can conclude that HOS does not have role to play in mediating this misconception but I think we can reflect that some shortcomings exist in how we might use HOS to provide a context for developing these ideas. The original intention of the unit was to use the law on constant proportions and the law of multiple proportions explained by Dalton's model of the atom to develop the relationship between theories and laws. In the evaluation of the unit, the teachers commented on the difficulty that students had with this part of the course. Remembering the compulsory nature of the course and the subsequent general population it is understandable how many students would have difficulty with this part of the course.

Perhaps, Hiero's problem could have been used to more explicitly develop the idea of a law of nature (density in this case) and how this law can be explained by a theory of matter. Students need an opportunity to recognize patterns in nature and then assign the regularity of the pattern to law status while a corresponding theory explains the law. It is concluded that much more time is necessary for students to carefully examine this relationship and many more activities are needed to carefully construct these ideas and their relationships.

Even though most students adhered to the hierarchy that proven theories become laws, in the interviews virtually all students stated that laws could also change in the future. In their study, Lederman and O'Malley (1990) reported similar conclusions. They found in their interviews that students did not use the word proof or proven to mean that scientific laws were absolute. In this study, almost all students also revealed in the interviews that they did not believe that laws were absolute, but they may change in the future. For example, Arlene states:

I: Is it possible that once we have a law, any law of science, is it possible that in the future the law, which was proven, might change?

Arlene: For sure, I mean, who knows what the future will bring. I mean, people predict, but who knows? I mean maybe we'll get more advanced, maybe we'll get less advanced, maybe we'll realize that everything we've been doing is wrong.

Other students thought laws could change only if something in the environment changed. For example,

I: You said that a law will always be true, is that for all time or is it possible that the law might change in the future?

Mia: Well, I guess it depends on like how our world develops. Like, if something in the atmosphere, something, then maybe gravity could change and, but as we know right now that those things will continually be the same until something else is discovered.

It may be that these students consider laws the way I've described robust theories. Robust theories have a considerable amount of supporting evidence, they are stable over time but they may also be subject to change with new evidence and insights. In such a case, it is the correct scientific terminology that must be overcome, likely over an extended period of time.

VNOS Question #4 Interpretation and Analysis

How are science and art similar? How are they different?

Questions #4 and #5 are intended to examine the role of creativity and imagination in science and are closely related to each other. Consequently, questions #4 and #5 are summarized together after the analysis for each question is presented.

Expert responses (Bell, 2001) believe that creativity permeates all aspects of the scientific process from the earliest conceptions, to the development and completion of experimentation, and in the interpretation of data and inference of theories and new ideas. Experts also do not adhere to a single scientific method but value different approaches to answering research questions. Interestingly, 78% of the experts in Bell's study used history of science vignettes to exemplify creativity and imagination.

Students possess a broad range of ideas about the role of creativity and imagination in science and art. Question #4 presented a unique challenge since students' naive views about creativity and imagination in science are often compounded by their naive views about art. Most students, in some way, considered art to be self-expression and science to be about the "real" world. However, some students claimed the opposite view that a rigidity in art is exemplified by painting within the lines and following the rules. One student suggested that "with science you can go anywhere with your thinking but art you have to follow teachers' guidelines for drawing". This was quite reminiscent of the famous Harry Chapin song “Flowers are Red” which tells the story of the little boy who loses his creativity when he is forced to paint all flowers red and all leaves green. Many students held other naive views of art, often describing a “crafts” point of view. This point of view was also reflected in some responses in terms of the purpose of art and science. Some students reported a difference in the purpose of each enterprise with science considered to be beneficial to humankind while art is for fun and recreation. Their responses often stated that “science is more real, art is fiction”, “science is more necessary and practical while art is for enjoyment” or “they are different because science helps mankind while art is a pleasure”.

The most naive view of creativity that can found in the students’ responses was that there was no role for creativity in science (-). Other extreme naive views (-) include a simple description of the content of each domain, that is, art is about paints and brushes and science is about biology and physics. A common naive view (-) described science as a compendium of facts and art as one’s feelings or expressions. Students often used phrases similar to ,“science is facts, art is opinions and expressing”, “art is an expression of feelings, in science you find the truth”, “in art there was no method but in science there was method”, or “art is free and individual, science is exact and precise”. It was also often stated that art was personal and emerged from within while science emerged from the outside. Some Students commented that “in art you are creating things, in science you are discovering things”. While we do recognize that in science there is a need for empirical evidence, it is not in the sense that our theories are “discovered” through our observations.

Some students recognized a role for creativity in science in terms of inventions and technological devices (like the telephone, the car, etc) and also in terms of ideas such as "dreaming up experiments" (+). However, students' often tempered their view of creativity in art and science by stating that "in art there are no rights or wrongs, but in science there can be".

Table 30 highlights some student responses with illustrative examples.

Table 30

Symbol	Comments:Q4	Illustrative Example
-	inconsistent answer, naive responses include: science is facts, art is expressions, content: science is biology, art is paint, science is discovered, art is expressions, the level of comparison is basic, pictures and diagrams are used	"in science pictures and diagrams are used and in art there are pictures/drawings" "science is facts, art is opinions and expressions" "art is more free and individual, while science is exact and precise"
+	Student recognizes that: creativity can play a role in both art and science, science has a grounding in the real world, provides example in context	"science and art are similar in that they are both expressions of thought"
++	Creativity plays a role in more than experimental design, it can be used in data analysis by creating patterns and explanations.	

Data Analysis Question Number Four

Based on coding

Table 31

Pre Test				
-	+-	+	++-	++
49	20	5	0	0
1	2	3	4	5
Group				

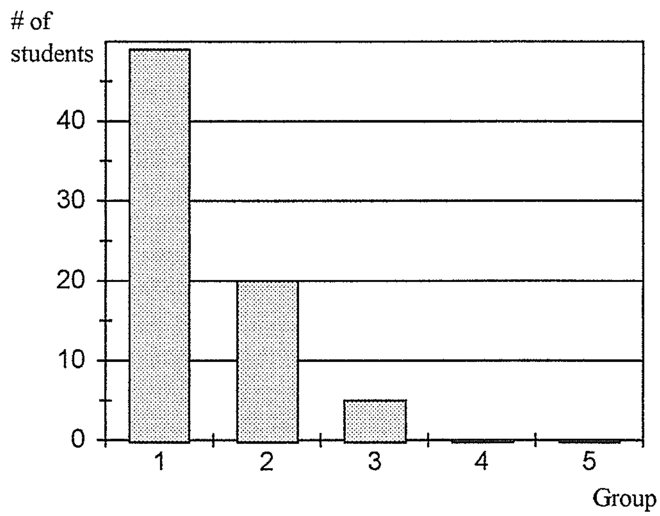

Figure 16

Table 32

Post Test				
-	+-	+	++-	++
25	30	18	0	1
1	2	3	4	5
Group				

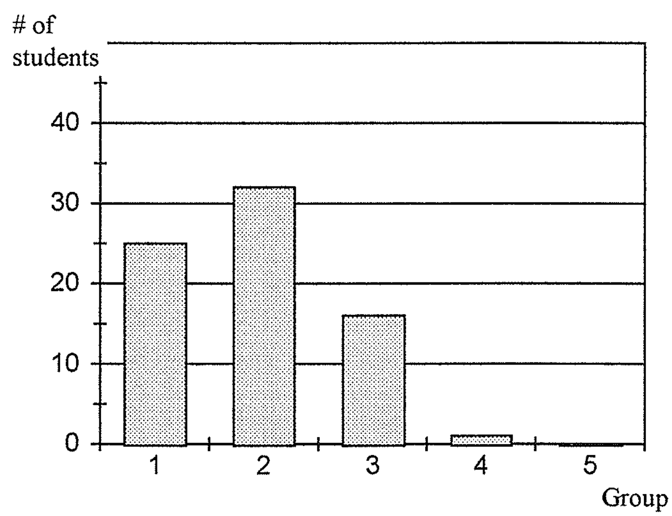

Figure 17

Before instruction, 0% (0 of 74) of the students held more informed views while after instruction only 1 % (1 of 74) held a more informed view. Additionally, 66 % (49/74) of the students initially held only negative views while post instruction 34 % (25/74) of the students maintained only negative views. Before instruction, 7 % (5 of 74) held positive views about the creative aspects of science while post instruction 21.6 % of the students held positive views. Also, post instruction 1 % (1 of 74) of the students held a more informed opinion with respect to the creative nature of science.

While it is difficult to assess the meaning of a change from -+ to + without examining the student's actual response, the graphs do give a visual representation of a reduction (from 49 to 25) of the naive view and an increase towards some more positive ideas. However, unlike questions #1 and #2 we do not find a general movement towards more informed views and only one student was identified as moving to a more informed view.

Each students' response on the pre and post tests were compared to determine if the student strengthened, positively changed, or had no change in their ideas. Students strengthen their ideas if they articulate their answer better and provide more meaningful examples and evidence. A student is determined to have positively changed their ideas if their views changed significantly or if they have added a positive view not previously expressed.

Table 33 shows that a total of 33 students (41 %) strengthened or changed their views positively. Unlike question #1, no students initially held more informed views of this aspect of NOS. Therefore, no adjustment for students with less informed views was undertaken.

Table 33

n = 74 models		
Strengthen View	Positive Change	No Change
17	16	41
21.6 %	18.9 %	59.5 %

The Role of History of Science

To what extent can we believe that the history of science aspect of the course plays a role in altering students' views of the nature of science with respect to creativity in science? This is a far more difficult task in question #4 than in the previous questions. In question #4, students were asked only, what are the similarities and differences in art and science? Many students provided personal views about the nature of art and simply compared them to their view of science. Consequently, no students provided any historical arguments to support their claims in the pretest and only four students provided a historical reference in the post-test. Three of the students made reference to the changing nature of the atom (or model of the atom) and one student cited Rutherford's experiment as creative. However, it is interesting to note that of the four students who provided historical references three of them made positive changes and one strengthened their view of the role of creativity in science.

VNOS Question #5 Interpretation and Analysis

Scientists perform experiments/investigations when trying to solve problems. Other than in the stage of planning and design, do scientists use their creativity and imagination in the process of performing these experiments/investigations? Please explain your answer and provide appropriate examples.

Expert responses (Bell, 2001) believe that creativity permeates all aspects of the scientific process from the earliest conceptions to the development and completion of experimentation, and in the interpretation of data and inference of theories and new ideas. Experts also do not adhere to a single scientific method but value different approaches to answering research questions. Interestingly, 78% of the experts in Bell's study used history of science vignettes to exemplify creativity and imagination.

Lederman and O'Malley (1990) reported that their interviews revealed that students believed most creativity occurred before the experimentation stage. They also found many students believed that during an experiment scientists adhered to a rigid scientific method. In this study, few students made specific references to the scientific method but they sometimes did refer to the exactness and precision of science and the necessity of logically figuring things out. For example, Cheryl writes that scientists "do have to use their creativity and imagination, but when trying to find an actual answer they must logically figure it out."

A naive response (-) to question #5 was used if students stated that scientists don't use creativity or they only use creativity and imagination to think up an experiment (that is, they restate the question: in the stages of planning and design).

In a positive emerging response students used a sense of creativity in an engineering way. That is, if a scientist was trying to do something, and couldn't get it to work, he could get an idea and try to fix it.(+) However, often the solution was of a trial and error or "tinkering" kind of approach. Creativity could also play a role in performing experiments when things go wrong if scientists proposed possible solutions, thought about what would happen, or thought creatively about possible outcomes (+). Students were considered to be more informed (++) if they provided both responses that is, they indicated that scientists used creativity to modify their experiment and they thought creatively about possible solutions not found in the original plan. Additionally, students were considered to be more informed if they believe that creative thinking permeated other aspects of science such as in the interpretation of the data (++). Table 34 highlights some student responses with illustrative examples.

Table 34

Symbol	Comments:Q1	Illustrative Example
-	inconsistent answer, naive responses include: don't use creativity or imagination, or only restates in the planning stage	"No they do not. The experiment must be controlled. Exact methods must be used to keep it controlled".
+	Students recognize that: creativity can play a role in performing experiments when things go wrong, to make adjustments, to propose possible solutions, think about what might happen	"if I try this than this might happen" "what caused something to happen, or what would happen"
++	Creativity plays a role in more than experimental design, it can be used in analysis by creating patterns, to think about the results of an experiment. to make changes during the experiment AND think about possible outcomes (both answers needed)	"once the experiment is completed, a great deal of imagination and creativity is used to interpret the data and come up with a conclusion"

Data Analysis Question Number Five

Based on coding

Table 35

Initial				
-	+-	+	++-	++
32	17	25	0	0
1	2	3	4	5
Group				

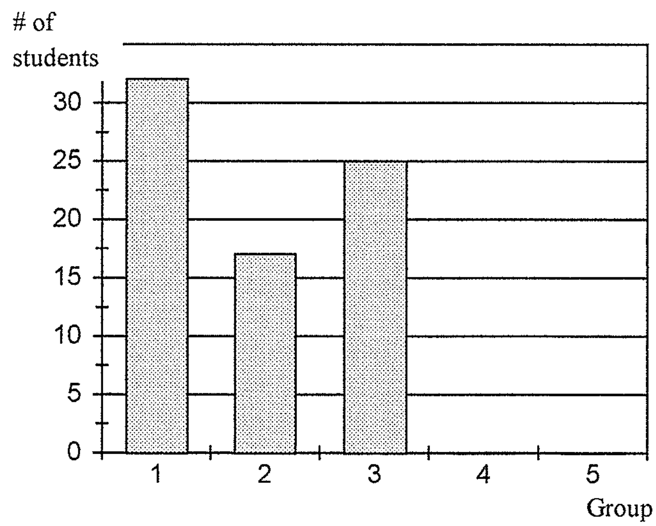

Figure 18

Table 36

Final				
-	+-	+	++-	++
22	18	30	0	4
1	2	3	4	5
Group				

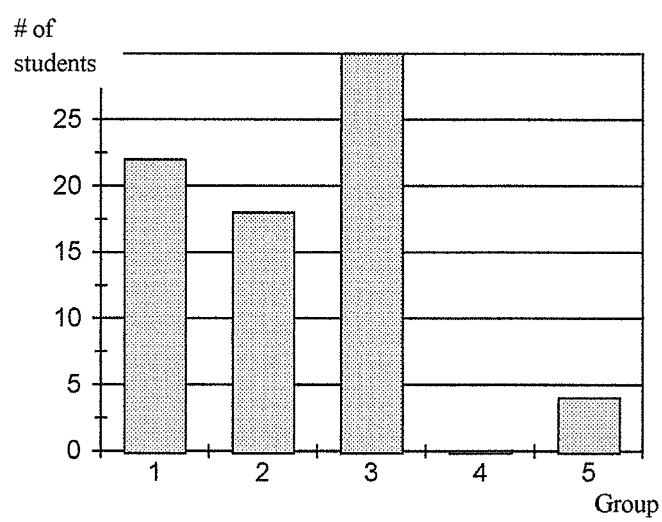

Figure 19

Before instruction, 0% (0 of 74) of the students held more informed views while after instruction 5 % (4 of 74) held more informed views. Additionally, 43 % (32/74) of the students initially held only negative views while post instruction 30 % (22/74) of the students maintained only negative views. Before instruction, 34 % (25 of 74) held positive views about the creative aspects of science while post instruction 41 % of the students held positive views. Also, post instruction 4 % (4 of 74) of the students held a more informed opinion with respect to the creative nature of science.

While it is difficult to assess the meaning of a change from -+ to + without examining the student's actual response, the graphs do give a visual representation of a reduction of the naive view towards some more positive ideas. Unlike questions #1 and #2 we do not find a general movement towards a more informed view as only four students were identified as moving to a more informed view.

Table 37 shows that a total of 22 students (30 %) strengthened or changed their views positively. Unlike question #1, no students initially held more informed views of this aspect of NOS. Therefore, no adjustment for students with less informed views was undertaken.

Table 37

n = 74		
Strengthen View	Positive Change	No Change
5	17	52
6.8 %	23.0 %	70.2 %

The Role of History of Science

To what extent can we believe that the history of science aspect of the course plays a role in altering students' views of the nature of science with respect to creativity in science?

Given the lower number of students who strengthened or positively changed their views, this is a far more difficult task in questions #4 and #5 than in the previous questions. In question #5, students were asked to explain their answers and provide examples. Students generally did a poorer job explaining their responses to question #5 than any other question. Question #5 also had the most no responses or "I don't understand" responses (n =5). All other questions combined had only 3 no responses. In terms of the types of evidence and examples provided by the students, question #5 also reflected a greater variety. Table 38 indicates the examples provided by the students.

Table 38

Evidence Cited	Pre	Post
No example or evidence given	61	51
Plum Pudding model	0	3
Rutherford gold foil experiment	0	4
Atom	2	10
Periodic Table	0	1
Lavoisier	0	2
Galileo	2	0
Inventions, technology	6	2
Chemicals	2	0
Hiero's experiment	0	1
Astronomy	0	1
Wright brothers	1	0
Cooking	1	0
Total (examples/evidence)	14	24

Two students provided more than one answer.

Table 39

	Example Only	Supporting Argument	Inappropriate Use
Pre	8	0	6
Post	14	6	4

Table 39 shows that in the pretest 19 % (14) of the students provided examples/evidence to support their answers. Of the 14 examples, 5 were considered to be historical examples (atom, Galileo, Wrights). In the pre-test, no students used their example as a supporting argument and six students used their example inappropriately. Students commonly listed their examples as creative inventions (cars, phones, medicine) as opposed to addressing the question of creativity in the process of performing an experiment. In the post-test, 32 % (24) of the students provided examples/evidence in their responses. Of the 24 examples, 21 were considered to be historical examples. Four students used their examples inappropriately, all four used the model of the atom to support creative ideas in the planning stages of an experiment and did not address scientists creativity while performing of the experiment. Four students who used historical examples demonstrated positive change and three students who used historical examples strengthened their ideas.

Summary Question #4 and #5

A large majority of the students (66 %) started the HDCM unit with naive views on the role of creativity and imagination in science as measured in question #4. After instruction this majority was significantly reduced (33 %), however, students' views about the role of creativity and imagination moved towards emerging views of NOS and failed to move towards a more informed view of NOS. Although progress was shown in the right direction these results are less significant than for questions #1 and #2. It may be that for the aspects of NOS pertaining to models, laws, and theories, the HDCM unit was more explicit in developing views. In the creativity aspect of NOS there were fewer opportunities in the HDCM for students to address the role of creativity in science. In order to provide students with an opportunity to address creativity and imagination in the HDCM unit they were asked to consider creativity in a journal assignment. The question was presented as:

> It has been said that science and technology, like literature, art, and music are creative manifestations of the human mind and spirit. Describe an example of technology which portrays the creative genius of humankind.

However, in their responses most students looked at creativity in terms of the wonder of technology and not in the creative genius of humankind. For example, in her journal assignment, one student responded that "its amazing how through a little cord you can hear someone's exact voice tones". In terms of recognizing the creative contributions of the human mind we might hope that the student could cite some of the original ideas which led to the development of the telephone (or any other technology). However, this form of recognition would require some background in the context of history. Sadly, without a historical base most students merely look at creativity in terms of the marvel of the machine as opposed to any awareness of the human contribution.

Other elements of instruction pertaining to creativity were much more implicit and the teachers were unable to provide examples of discussions that students had pertaining to the role of creativity in science. These results support previous research by Lederman, which suggests that teaching aspects of NOS must be explicit. I would add that this explicit nature should include multiple opportunities for students to revisit their ideas and the ideas of scientists in a progressively more sophisticated manner. For example, in the future we could provide these students with some activities and opportunities to move towards a more informed view by considering more explicitly the creativity one might find during the course of an experiment or in interpretation of data and results. Indeed, this is a problematic area in science education. Most school science labs allow for no creativity in the interpretation of experimental results. Students typically saw the thinking up of a theory or an experiment as being creative, but after that the scientist was required to follow a more precise procedure. In the interviews, some students suggested that once the experimental procedure began there was no room left for creativity. For example:

> Aaron: Well, they have to make sure it is a controlled experiment, so they can't sort of say, it might be neat to try this.
>
> Sacha: I think, the beginning stages are creative and once you get involved in science and stuff it's more factual.

It does seems apparent that school laboratory procedures stymie the students' view of creativity. In her interview, Molly also states why she believes that creativity can be found in ideas but not in technique, especially in school science.

> "I think that often the ideas can be more creative than the technique because when we do science labs Mr. A doesn't tell us, ok, I want you to be really creative with this experiment, like it's exact and you have to record the information properly or you are not going to get accurate results. So, I think that the actual doing it, and coming up with the way to do it can be creative but when you are recording the information and connecting things and pulling stuff together, it's important to not be too creative, but to be exact".

I am not suggesting that experimental procedure not be precise or exact but that the "step by step" instructions that students are given hides the errors and dead ends that often lead scientists to develop greater understanding. One possible solution to this could be to use Fermi type problems which have no correct answers but require the student to provide a detailed rationale to defend their answers.

On the other hand, some students did use historical examples to support their answers and in some cases the historical vignettes did seem to make an impression. One student summarized her admiration of the clever nature of Lavoisier's experiments.

> "Yes, they have to be creative like Lavoisier, he was the first guy I ever heard of who suffocated birds, and then lit candles. You have to be very cunning about finding new ways to prove or disprove a law".

Question #7 Students Attitudes and the role of History of Science

Interpretation and Analysis

What role do you think the history of science may play helping you to understand models and theories in science?

There has been many detailed rationale for the inclusion of the history of science in science education (Monk and Osborne, 1997; Mathews, 1989; Winchester, 1989). However, to the researchers' knowledge no one has yet to ask the students what they think. The intention of question #7 was to survey students' attitudes towards the inclusion of history of science. Outstanding questions before the research included, "Would teenage students be turned off and disinterested in the history of science?", "Would the students consider the history of science to be merely an add-on", or "Would the students see the history of science as a meaningful pedagogical strategy?

Students' responses to question #7 were reviewed and coded according to the reasons they provided for their responses. In their written responses, most students offered more than one rationale for the role of HOS and a few students offered as many as four different responses. The responses were grouped into common categories and table 40 summarizes students' views on the role of history of science in their science education.

Table 40

#	Positive Views	n	#	Negative Views	n
1	Helps to understand more and/or better, makes you think	52	1	It is easy to get the models confused with the right one.	4
2	Shows how we got to today's knowledge, why we view our theories the way we do, the progression of our theories and ideas from their origins	34	2	It helps but I would rather learn from front to back.	1
3	To learn other people's views, their past experiences, how many people contributed and help develop science	19			
4	To understand and learn from past mistakes	19			
5	To learn the basics, a foundation and prior knowledge, early models easier to understand but still correct in many ways	14			
6	Our ideas can expand, we can build new ideas for the future, we can advance and progress	11			
7	Help to realize tentativeness of science	5			
8	Provided something to compare to today's ideas	4			
	Total positive views	158		Total Negative Views	5

Summary of Question #7

The majority of students reported that the historical development helped them to understand more and/or better and that it made them reflect on their work. Only three students indicated negative opinions towards the inclusion of HOS and these responses seemed to be more concerned with information overload (too many models to remember) than with any historical content. In fact, one of these students overwhelmingly endorsed the inclusion of the history of science in the unit and at the end of the unit commented

> Molly: I don't think I understood why we were learning about historical people, like I was thinking, why do I need to know this, it was thousands of years ago but I think I've appreciated it at the very end of the unit after I had done all of it, it kind of, fit into place better

Since students averaged more than two reasons per person for the inclusion of HOS we view these results as extremely encouraging. Although some students seemed neutral in the interviews and in the written responses, a number of students enthusiastically endorsed the role of HOS for a variety of reasons. Some students simply found different aspects of the historical perspective engaging. When asked what he found interesting, Matt replied, "The guy who was missing his nose, Tycho something" and many students enjoyed their research of the alchemists as different from their past experiences.

> Inessa: Although, although, the alchemists pretty much based their ideas on science, it's something that you wouldn't generally be learning about.

A number of students indicated that in their previous instruction they were just told what to believe and were provided no reasons to believe. In her interview, Erin proposed the "flat earth" as a scientific theory that had been disproved. When I asked what made her believe in a spherical earth, she replied, "Exactly, that's what I want to know!" Molly summarizes her feelings about the "final form" science that is commonly presented by textbooks and teachers.

> Molly: You are telling me that this is the atom but you could have made it up sitting at your desk right now. Like it is nice to know where things came from in the first place and seeing how it has progressed over time. It makes you feel more like it is worth learning about it, it makes it more interesting when you know have far it's come, and it helps you to appreciate what you have right then more.

And other students like Erin began to see the "big picture" and the relationship between evidence and theories.

> Rita: Um, I think it was basically the entire unit that just made everything a lot clearer, I didn't necessarily understand it all. But I understood there were facts, you know, backing up the theories and the things that were being put forward to us.

Students also commented on the fact that history of science brought people into the science classroom reflecting the "humanistic perspective" argument for the inclusion of the history of science.

> Molly: I mean it is really interesting to see the different viewpoints, how people back then thought differently and how we think now.

> Inessa: It is much more of an educated idea. I think, I had learned about science, I had learned different situations, different laws but I think this year I learned a lot more about, about the history of science and people that were involved in science. There was a lot

of stuff about people and how they contributed to science and I found that really good because last year we didn't learn anything about people

Arlene: Um, I've gained more knowledge for sure, learned more about the people, a lot more about the past in science and alchemy, you know, how we've matured in our technology and models and theories, and how that has all affected us.

Surprisingly to the researcher, few students expressed negative attitudes towards the history of science. However, a few students seemed to prefer to the "tell me and I'll tell you" mode of understanding. Andrea and her friend Lana were reported by their teacher as being quite anxious about just learning the "correct" version of science. In her interview Andrea claimed that "All we really need to know now is what they use now and what's right". Lana outlined the source of their frustration

Lana: My friend Andrea and I, you are going to interview her too, got very frustrated by the fact that we would learn a model and think that was what we were supposed to know, and then realize that there was another one that we had to learn. And just, we would get really confused with all the information. But we, I don't know. we thought that if we worked from the end of the unit and learned what we had to know and what was true for now and work backwards it might have made more sense. It made sense all in the end, it might have been, like it was well set up and everything but maybe if the teacher had told us, no this isn't the one you had to know, this is just where they were at this point in history. It might have just been the way it was taught to us. Cause it was **good** (her emphasis) to know all the history, to know why the one was the way it was now. It was just not knowing whether this was the one we needed to learn.

From their responses, the two girls did not seem to be concerned with the historical content as opposed to the amount of information, and how they were to synthesize that information. In fact, when asked to compare her understanding at the beginning of the course with her understanding at the end of the course Lana noted

> Lana: I think that they were the same but I understood why at the end of it. Like to me, my things look the same I just have more examples of this at the beginning but I didn't understand why, it was like words at the beginning, at the end I understood why.

Student Journals

Throughout the unit, students were asked to keep a NOS journal and reflect upon some NOS questions (like the question on creativity described earlier). At the beginning of the course students made a concept map to illustrate their understanding of "What is Science". At the end of the course students were asked to address the same question with another concept map. In the interviews students were asked to compare their concept maps and their understanding of "What is Science" before and after the unit. Typically students described science in terms (words) of factual content and in the end they began to outline a bigger picture of science which included terms, such as models, laws, and theories, used to think about science.

> Nina: In the beginning Mr. C would talk to us about it, it was just like, let's just do what he is telling us to do, words, it was just words,

> Aaron: I think I see that science is not so cut and dry like it used to be. Before this course I was always taught, these are the facts this is true, and now I see that a lot of the stuff that we know is developing information and we are not quite sure of many things but we're sort of, as we go we learn more.

Anna: More complex, I just, I always thought that it was just scientists doing experiments that you know, may have not always work out. But now I think people knew what they were doing, trying to diverse their culture and their society and the bigger aspect on the whole universe, was going on. So, ah, yea, they were trying to bring ideas into their societies, bring knowledge.

Perhaps the most powerful statement about their feelings toward science before and after the unit were expressed by Rita, a student who considered herself artistic and had no intentions to study science beyond the mandatory requirements.

Rita: Um, well, before I thought that is was just something that we had to learn, and you can kind of get that, you can kind of take that from my first journal entry I wasn't enthusiastic about it at all because I mean, you know what is science, it was the first day of school, well like science is boring, so it was very, every since we started, I can't, like I said before I can't remember science before grade seven, and so, until now I never really enjoyed science, and learning about minerals and alloys and that kind of stuff just kind of got to me, you know, biology, it really got to me. I just, I didn't understand it, I, you know, I wasn't clear about everything, but I figured ok well, science is pretty complicated, so if it's unclear it's probably not going to get much clearer, but this year it's changed a lot, I mean, like the first time you asked me that question how is art and science different I said well, there completely and totally different things, but now because I'm more the artistic type I'm learning and understanding how art can be related to science and vice versa, so, I mean it's, it's changed a lot, it's gotten pretty interesting, even though I don't understand a lot of the stuff, I like, you know the equations and stuff like that, I'm sure I'll never understand them, that's fine because I'm not going into science, it's gotten a lot more interesting and I'm understanding now, I'm understanding better, why things are they way they are and why, well I'm understanding basically all the answers to the questions that are asked and, you know, the ideas that are presented in your average science class so it's changed a lot, it's changed for the better, which is a good thing.

Assessing the Teacher's Role

The teacher plays a critical role in the success of any curriculum. It has been argued in this thesis that the curriculum must first be an "enabler" for NOS outcomes to be achieved. Then, using a sound pedagogical methodology which includes a history of science context, and inquiry and constructivist strategies that most teachers will be able to overcome the constraints of the system and, if required, their own background in NOS. In this study, although no formal evaluation was made, the three teachers demonstrated individual differences. One teacher embraced all parts of the curriculum with a great deal of enthusiasm, another emphasized certain parts, and another found time to complete the historical aspects but continued to emphasize strict content coverage. Naturally, we should address the question, "how do these individual differences influence the students' understanding of NOS"?

First, we must remember that all students and the teachers had a set of identical class frame notes that they followed. In their evaluations the teachers reported that few of the exercises were left out of the instruction.[120] They did report spending varying amounts of time on some aspects of the course but in the end, all three teachers went past the allocated time by at least one week.

In order to examine if there were any class differences, I examined the data for questions #1 and #7. Question #1 was selected because of the number of students who made progress in their understanding of the nature of science and the number of historical references that were made. Question #7 was selected because it helps identify

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120 In one case, the decomposition of water lab was omitted (but described).

the students' attitude toward the inclusion of the history of science in their course.

Question #1 is broken down by teacher in table 41 and graph (figure 20) to indicate pre and post test results.

Table 41

Question #1 Pre-test Results	Teacher A	Teacher B	Teacher C
-	3	4	6
+-	6	3	8
+	2	12	13
++-	5	0	4
++	4	1	3
	n = 20	n = 20	n = 34

Figure 20: Pre-Test Results by Teacher

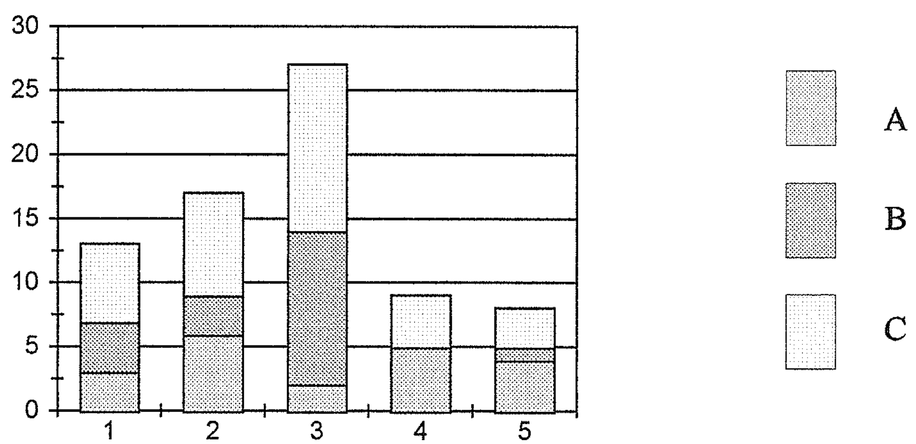
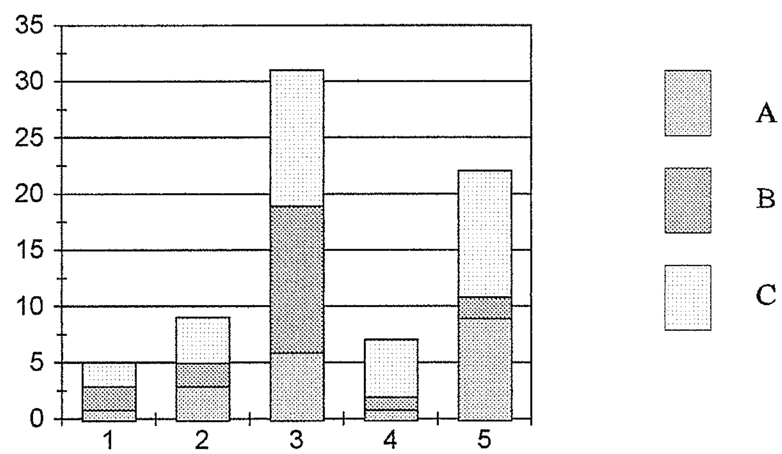


Table 42:

Question #1 Post-test Results	Teacher A	Teacher B	Teacher C
-	1	2	3
+-	3	2	4
+	6	13	12
++-	1	1	5
++	9	2	11

Figure 21 Post-test results by teacher



In the post-test data for question #1, all classes are shown to move towards the upper end of the scale. The number of students who made progress by strengthening or positively changing their views using historical examples are shown in table 43.

Table 43

Strengthen or Positive Change with Historical Reference n = 29		
Teacher A	Teacher B	Teacher C
9	5	15

These results again indicate that a fairly close match between classes A and C with class B slightly behind. Again, in consideration of the compulsory nature of the course and individual differences this slight variability should not be surprising. The data seems to indicate that individual teacher differences did not affect the understanding of the nature of science when the teachers followed the same curriculum.

The results of question #7 were tabulated to determine if the students' attitudes toward the inclusion of the history of science differed from class to class. Table 44 shows that on average class C had a slightly higher positive response rate toward the inclusion of the history of science. The variation is small enough that we may conclude that the students' attitudes were consistent across all of the classes. However, we should note that these were the classes that dramatized the history of science in their "day in the life of an alchemist" videos.

Table 44

Group (n)	Positive responses	Average per person
A (20)	37	1.9
B (20)	38	1.9
C (34)	79	2.3

In their evaluations of the unit all teachers reported that it was a bit too long. They also reported that the chemical bonding unit was difficult for the students. I would readily concur with their assessment. The chemical bonding unit could easily be left for the next chemistry course as a means to revisit the atom at a more challenging level. This would also solve the time problem. However, the only reason this part was included in the HDCM is because it is mandated by the provincial curriculum and the results here seem to support the view that covering less material, more comprehensively is better for the students.

The teachers and students enjoyed the lab exercises. It was reported that the equipment was simple to use and "well laid out" and that the students worked well with these labs. One teacher commented how they "were clearly connected to the concepts covered in the material." On Avagadro's hypothesis and the addition of equal volumes it was reported that "the students figured out how it could work before I could finish. Talk about being right with you!".

On another, important, positive note, one teacher reported significant personal growth in understanding the nature of science. As his understanding and enthusiasm for the topic increased, he commented "that students were swept along with me as I discovered how to show them the nature of science." As he was compelled to address the nature of science in the unit, he developed his own thinking in areas he had not previously considered to be important. He reflected that

> "As mentioned, my whole thinking about how to present science was challenged. The discussion about what is truth allowed me to move students through ideas I never dreamed as a part of science. I was also encouraged to challenge many of their ideas about absolute truth and sources of truth. I plan to expand this area to include biases, historical/cultural factors, stake holders, and world views..as a final comment, I would like to describe my time working in this study as one of the most beneficial professional development exercises in my young career."

One of the greatest concerns in the literature has been the lack of the teacher's understanding of NOS and the relatively poor background that they have in the history and philosophy of science. It appears that an additional benefit of the HDCM unit and the explicit nature of the NOS outcomes is that teachers, when confronted with the nature of science, can experience a considerable amount of growth which can greatly enhance and improve their own teaching. We should not be surprised at this outcome. Teachers have been learning and growing with their students for years, why not in the nature of science?

Chapter VII

Conclusion

This thesis has advanced a curriculum that explicitly enables NOS outcomes to be integrated within the Manitoba grade ten science curriculum. It was argued that an historical development of conceptual models (HDCM) provides a context for achieving NOS outcomes. The purpose of the research was to assess students' understanding of the nature of science and to determine if this understanding is influenced by the HDCM unit. The research also investigated students' attitudes towards the inclusion of the history of science in their science course by asking students what role they believe the history of science may play in understanding theories and models in science. The research was guided by the following questions:

1. How does the historical development of conceptual models (in particular, the model of the atom) influence students' conceptions of the nature of science?

2. What specific aspects of the NOS are influenced by the integration of history of science in science instruction?

3. What are the students' attitudes towards the inclusion of the history of science in their learning of scientific models and theories?

The analysis of the VNOS pre and post-tests, complemented by the interviews, was used to investigate several aspects of students' understanding of NOS including the tentativeness of theories (Question #1), the role of models and evidence (Question #2), the relationship between theories and laws (Question #3), and the role of creativity and imagination (Question #4 and #5). The findings of this study indicate that the historical development of conceptual models (in particular, the model of the atom) influenced students' conceptions of the nature of science in an improved understanding of the tentativeness of theories, and the role of models and evidence in science.

In terms of students' understanding of tentativeness and scientific theories (VNOS Question #1), the research results (should show explicit links to the findings) demonstrate a significant shift in students views towards the development of more informed ideas. When the data were adjusted to consider only those students who entered the course with less than an informed understanding of NOS, we find that a significant majority, sixty-five percent (65%), strengthened or positively changed their ideas. Further, forty-four percent (44%) of students who initially held less informed views, strengthened or positively changed their views using historical references to support their responses.

Similar results were found in students' understanding of the role of models and evidence (VNOS Question #2). The majority of students (57%) in question #2 strengthened or positively changed their views about the nature of the atom and a significant number (43 %) used historical examples to support their responses. Further, many students who made no reference to historical examples in question #1 and/or question #2, reflected an understanding of the historical nature of the course in their responses to other questions.

These results should be viewed as significant, especially in light of the manner in which students employed their examples in the VNOS post-test and subsequent interviews. Previous research (Lederman & O'Malley, 1990; Aikenhead, 1987) found that students were unable to indicate the sources of their beliefs when they answered NOS questions. Typically, these responses reflected factual content learned by authority in school science as students failed to develop adequate evidence to answer the questions "how do we know" and "what are the reasons to believe"? Monk and Osborne (1997) recommended that a pedagogical strategy which focused on these questions not only supports the learning of science but also the learning about science.

The results of this study show that students used examples (including historical examples) to help justify their beliefs. Sometimes, students simply reported an example by name or used the example incorrectly in their response. Alternately, in the preferred response, students used their examples as support for their beliefs by expanding on and relating the salient details of the example to the question being asked. After instruction in the HDCM unit, the number of historical examples cited by students increased substantially and many more students began to use historical examples as supporting arguments. It was also found that fewer students used their examples in an incorrect or naive way. In this way, the HDCM unit advanced students understanding of models and theories beyond earlier studies. Additionally, the significant results from questions #1 and #2 on models and theories also supports Monk and Osborne's (1997) contention that students are learning about science.

There are several reasons to believe that many of the students who did not include historical references in their responses were also influenced by the historical content of the unit. In the interviews, some students who did not include historical examples in their written VNOS responses, used historical arguments in the interview to clarify their answers. Unlike in Irwin's (2000) study, the interviewer in this study was an independent observer and students freely provided historical examples when they were asked to expand on their beliefs. Although we have no way of knowing how many students (without interviewing all of the students) could have used historical examples as supporting arguments, we can conclude that the percentage of students who were influenced by the history of science is actually higher than the data indicate. Additionally, the student profiles indicate that many students used historical references in their responses to other questions, suggesting an overall influence of the historical perspective for the majority of students.

I am, therefore, confident that the HDCM unit was a successful means to improve students' understanding of models, theories, evidence, and the tentativeness of science as measured by questions #1 and #2 in the VNOS. The manner in which students employed their examples in the post-test strongly indicates that the historical content of the unit accounts for this change. There are several reasons why we might expect this outcome. According to Hodson's ideas (1988), the historical development of the model of the atom seems to provide students with opportunities to consider historical ideas and experiments in terms of the development of tentative models. Evidence to support the model is considered and evidence which is discrepant to the model is confronted. In this way, students are naturally, and explicitly, introduced to the tentativeness of scientific theories, and the role of models and evidence in science. In general, students began to understand the nature of models and the kinds of experiments and indirect evidence that scientists use to evaluate their models. In particular, Rutherford's experiment seemed to provide many students with a plausible explanation for the basic structure of the atom.

The positive results of questions #1 and #2 can not be extended to the relationship between theories and laws (VNOS question #3), and the role of creativity and imagination in science (VNOS question #4 and #5). The data does show that there is an overall shift in students' understanding of the relationship between theory and laws towards positive ideas about theories and laws. However, students generally increased their understanding of theories or laws independent of each other and failed to make little or no improvement on understanding the relationship between theories and laws. McComas (1996) has indicated that the view that theories advance to laws is extremely pervasive. While the relationship between theories and laws was dealt with explicitly in the unit, it appears that much more effort is required to overcome this tenacious misconception. The public understanding of theories and laws may also have a significant influence in students' understanding and belief of laws. In common usage the phrase "it's just a theory" is often applied to a speculative idea. In order to combat this influence, it is suggested that adjectives be adopted to describe a spectrum of theories from speculative to robust. Speculative theories are potential explanations with little or no supporting evidence while robust theories have a considerable amount of supporting evidence, remain stable over time, but may also be subject to change with new evidence and insights.

Even though it was found that most students continued to adhere to a hierarchy that proven theories become laws, the interviews revealed that virtually all students believed that laws could also change in the future. In their study, Lederman and O'Malley (1990) reported similar conclusions. They found in their interviews that students did not use the word proof to mean that scientific laws were absolute. In this study, almost all students stated in the interview that they did not believe that laws were absolute, but that they may change in the future. These students seem to consider laws in the same way we might consider robust theories but without the corresponding support of evidence.

The HDCM unit also did not yield significant results in advancing students understandings of the creative and imaginative aspects of NOS. In the pre-test, a significant majority of the students (66 %) started the HDCM unit with naive views on the role of creativity and imagination in science. After instruction, this majority was reduced by just over half to 32 %. However, students' views about the role of creativity and imagination only advanced towards emerging views of NOS and failed to move towards a more informed view of NOS. On the other hand, on a case by case basis, some students did use historical examples to support their answers about the role of creativity and imagination. Students expressed admiration for the ingenuity and cleverness of Lavoisier's and Rutherford's experiments, and the shrewdness of Archimedes solution to Hiero's problem.

Although progress was shown in the right direction, these results must be considered less significant than the results of questions #1 and #2. It may be that for the aspects of NOS pertaining to models, laws, and theories, the HDCM unit was more explicit in developing views, while fewer opportunities existed in the HDCM unit for students to address the role of creativity in science. Elements of the instructional unit pertaining to creativity were probably less explicit than intended. The teachers were unable to provide examples of discussions that engaged students in understanding the role of creativity and imagination in science. These results support previous research by Lederman, which suggests that teaching aspects of NOS must be made explicit. Most students looked at creativity in terms of their own experience with the wonder of technology. It was not uncommon for a student to respond that technological devices (like the telephone) were "amazing". Additional strategies need to be developed to extend this wonder of technology to the wonder of human ideas and contributions to science. For example, in the future we could provide these students with activities and opportunities to move towards a more informed view by considering more explicitly the creativity one might experience during the course of an experiment, or in interpretation of data and results. Indeed, this is a problematic area in science education as school science labs allow for no creativity in the interpretation of experimental results. More open ended opportunities are necessary for students to use their own imagination and ingenuity to reflect the errors and dead ends that often lead scientists to develop greater understanding.

Unquestionably, students possessed positive attitudes towards the inclusion of the history of science in their curriculum. The HDCM unit presented a more humanistic view of science to the students which was reflected in their interest, motivation, and responses to the curriculum. We should view this result as extremely positive for future curriculum development in this area.

The majority of students reported that the historical development helped them to understand more and/or better and that it made them reflect on their own work. Only three students indicated negative opinions towards the inclusion of history of science and these responses seemed to be more concerned with information overload (too many models to remember) than with any historical content.

Since students averaged more than two reasons per person for the inclusion of history of science we view these results as extremely encouraging. Although some students seemed neutral in the interviews and in the written responses, a number of students enthusiastically endorsed the role of history of science for a variety of reasons. Some students simply found different aspects of the historical perspective engaging whether it was the uniqueness of Lavoisier's experiments, the ingenuity of Rutherford, or the activities involved in the "day in the life of an alchemist". Students' comments that the history of science brought people into the science classroom supports the "humanistic perspective" argument for the inclusion of the history of science advocated by many educators (Mathews, 1994; Stinner, 1994a; Winchester, 1989). The different viewpoints and ideas of different people at different times in history and the progression of our theories and ideas from their origins was often cited by students as beneficial to their understanding of science. Students also expressed an interest in "how we got to today's knowledge" and why we view our theories the way we do. Students gained respect for other people's views, their past experiences, and how different people contributed to the development of scientific ideas. Some students even recognized that early models are still correct in many ways, thus helping to re-enforce the tentative nature of science What was surprising to the researcher was that not many students expressed negative attitudes towards the history of science. However, a few students did seem to prefer learning only the "correct" version of science. From their responses, these students did not seem to resent the historical content but remained opposed to the amount of information, and how they were to synthesize that information. However, in spite of their resistance, these students also seemed to recognize and reap some benefits from an historical approach. One of these students, when asked to compare her understanding at the beginning of the course with her understanding at the end of the course noted "it was like words at the beginning, but at the end I understood why".

All of the teachers reported in their evaluations that the unit was a bit too long. Since the teachers and students enjoyed working with the labs, some modification of the content is necessary to provide realistic timelines. Importantly, one teacher reflected on significant personal growth in understanding the nature of science. It seems that participation in the unit compelled him to address the nature of science for the first time as he developed his own thinking in areas he had not previously considered to be important. In light of the research on teachers understanding of NOS this should be interpreted as a very significant result. When the curriculum explicitly enables NOS outcomes, teachers will begin to reflect on the treatment of those outcomes, consequently improving their own understanding of NOS. I consider the teacher's growth to be perhaps the most compelling outcome of the research.

Limitations of the Study

There are several limitations to the study that should be noted. All teachers reported that they needed additional time to complete the unit and that they rushed towards the end to finish. One teacher commented that he felt he could manage better if he taught the unit a second time. This is not an unexpected result. Most teachers achieve a certain comfort level as they teach the same course a second and a third time. In this stage of teaching, the teacher learns the material better, becomes more familiar with their student's prior knowledge, and has time to work out the imperfections in laboratories and student activities. Consequently, I would expect even better results if the teachers had additional experience and adequate time to complete the course.

In terms of the assessment, the VNOS test is relatively new and research into the test is continuing, especially with respect to improving the language on the test for younger students. Some of the items, such as the creative aspects of NOS in experimentation, could prove to be a little too complex for younger students. Recently, a new model of the VNOS has been proposed by Abd-El-Khalick (2002) who is interested in examining the developmental aspects of understanding NOS. In his preliminary study, it appears that as students progress through high school (from grade nine to grade twelve), their adherence and understanding of a rigid methodology in science increases and the creative aspects of NOS actually decrease to the point where they virtually disappear.

Some concern might be expressed for a lack of a control group in the study. In this research, it was logistically impossible to secure a control group. However, the consensus of previous studies suggests that students possess naive ideas on understanding NOS (Lederman, 1992). Further, these naive ideas are found in students of all ages from middle school to university students. Thus, we should not expect the development of an adequate understanding of NOS to be achieved through the current practice of implicit instruction. The research also clearly shows that there are no strategies which generate significant changes in students' understanding of NOS without explicit instruction (Abd-El-Khalic, 1998; Abd-El-Khalick & Lederman, 2000; Schwartz, Lederman & Thompson, 2001) .

What is of concern in this study is the source of any gains in students' understanding of NOS. In order to determine the source of students' beliefs an analysis was done of the students' supporting arguments. As previously indicated, students used historical examples as supporting arguments for their beliefs in NOS much more frequently after instruction than before. The only possible source of this development is the course itself.

Implications for Further Study

The HDCM unit is, to the best of the author's knowledge, the first attempt to integrate a historical context over a significant developmental period of time. Further research is needed to build on this endeavor. The development period could be extended even further in the future to investigate the change in students' understanding of NOS over a period of years. Future research projects might also investigate other historical models such as the wave and particle models of light.

In this study, the HDCM unit showed good success with advancing students' understanding of models, laws, and theories and promoting the use of supporting arguments to answer the questions "what makes us believe?" and "how do we know?". However, the view that theories advance to a law status was still widely maintained and appears to be quite tenacious. Additional attention needs to be placed on this relationship as well as promoting the development of activities and resources that clearly differentiate between laws and theories.

Several aspects of the creative nature of science also merit additional attention. Students views on the relationship between art and science were often conflicted with their naive views on art itself. Moreover, the sources of these beliefs need to be understood better with special attention to the role of the students' prior knowledge. It is quite possible, in terms of advancing students' understanding of NOS, that we should opt for more modest goals and that future research consider isolating the creative aspects, and the corresponding assessment, from the NOS aspects of models, laws, and theories.

This study also indicated a wide acceptance of the integration of the history of science with regular content instruction. Further studies could begin to focus on particular aspects of the history of science that students find attractive and motivating. Students enjoyed the hands-on activities in a historical context and more activities need to be elaborated to provide students, especially younger students, with meaningful hands-on history of science experiences. Since recent reforms have stated goals with respect to the nature and history of science, further research could focus on curriculum development implemented by the provinces and how this development reflects the stated goals.

Given the apparent growth in the understanding of NOS that one of the teacher's developed, additional research could be pursued in this area. It would be particularly relevant to determine that if by explicitly enabling NOS outcomes in a formal curriculum if teachers would also show gains in their understandings of NOS. Finally, research could also focus on how any improvement in a teacher's understanding of NOS transfers to his or her teaching, and subsequently to the students' understanding of NOS.

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Appendix A

HDCM Outline: The Atomic Model of Matter

Unit 1: What is Science?
Unit 2: The Search Begins.
Unit 3: The Particle Model of Matter.
Unit 4: The Elements and the Atomic Model.

Unit 1: What is Science?

MB Curriculum Outcomes	Topic	Nature of Science	Comments on Instruction
	What is Science?	Define and give examples of Facts, Models, Laws, Theories	Concept map to tap into student's prior knowledge. Model of the solar system is used as an example of a model that students are familiar with.
	Story of Tycho Brahe and Johanne Kepler.	Contrast observation and inference. Observation is theory laden and contextual.	
	Mystery container	Models, observation, inference	Word Cycles are used to re-enforce vocabulary.
	Science and Technology	Science is creative. Domain of science.	Journal reflections.
Lab Safety	Lab Safety	Observation in classroom. Inference of potential safety hazards.	WHMIS as required.

Unit 2: The Search Begins

MB Curriculum Outcomes	Topic	Nature of Science	Comments
	What is matter made of?	Introduction of proto-model.	Students list different possible kinds of matter (wood, water, porridge) and their characteristics (hard, wet, sticky)
	Zeno's Paradox		To introduce discrete and continuous concepts.
	Early ideas of matter. Pythagoras, Democritus, Aristotle.	Introduction of competing models.	Student's compare and contrast their ideas of the % of earth, air, fire, water that make up different types of matter.
	Alchemy. Zosimos' experiment on transmutation.	Processes of science. Taking stuff apart to find the smallest piece of matter or to learn the secrets of the philosophers stone. Bacon and Inductive science.	Word Cycle - A day in the life of an alchemist. Student's research alchemy. Zosimos' experiment is later revisited by Lavoisier.
Characteristic Properties	Experiment - Density	Develop skills needed to take matter apart. Processes of the alchemists.	
Density	Hiero's Tale		Provides a motivating context. Referred to later for relative mass.

Mixtures	Boiling, Freezing, Melting Points	Develop skills needed to take matter apart. Processes of the alchemists.	
Compounds	Experiment - Decomposition of Sodium Chlorate	Explained by the model of phlogiston.	
Conservation of mass	Experiment - Combustion of Copper	Discrepant event: The problem of combustion and respiration. Components (facts, model, laws, consistency) of Lavoisier's theory of oxygen.	Students outline the theory of oxygen in terms of facts, models, laws, and theories.
Elements		Lavoisier's elements.	

Unit 3: The Particle Model of Matter

MB Curriculum Outcomes	Topic	Nature of Science	Comments
	A new approach to our thinking. The particle model of matter.	Inductive vs. Deductive thinking.	Invent the model and deduce the consequences.
Model of the atom	Dalton's Model	Simple explanation of mixtures, compounds, elements.	
	Law of Constant and Multiple Proportion	Explained by Dalton's model.	
	Avogadro's hypothesis. Law of Combining Volumes Decomposition of water.	Discrepant event. Give example of model, law, facts, discrepant event for Dalton's theory of matter.	Decomposition of water is revisited later to introduce the electric atom.

Unit 4: The Elements and The Atomic Model

MB Curriculum Outcomes	Topic	Nature of Science	Comments
	Relative and atomic mass.		Recall Hiero's tale to introduce relative mass.
Periodic Table	Mendelev's Periodic table.		
Model of the atom	Dalton's problem: The Electric Atom	Consistency of scientific theories.	Faraday's experiments.
	Thomson's plum pudding.	Explains electric nature of the atom.	
	Rutherford's experiment and "solar system" model.	Discrepant event to Thomson's predictions for scattering.	Models are considered based on their explanations and predictions.
	Japanese model	Cultural.	
	Flames tests and spectra.	Discrepant to Rutherford's model.	
	The Bohr model.	Explains spectra of hydrogen atom. Explains bonding.	
Chemical formulae	Chemical formulae and compounds.		Using Bohr Model.
	The Quantum Model.	Re-introduces the discrete/continuou s question. The tentative nature of science.	Science continues.

Appendix B - Administrator's Letter of Permission

Dear *(administrator)*

(teacher) has expressed an interest in participating in my research project for Science 20S students. In the new Manitoba science curriculum, the understanding of the nature of science is a primary goal. However, it is left to the teacher to provide an appropriate context to achieve this goal. This research project uses the historical development of conceptual models as a context to improve understanding of the nature of science. The program, which is based on the Science 20S chemistry unit, has been developed by me. I am a PhD graduate student in the Faculty of Education at the University of Manitoba, and this study will provide me with data for my doctoral dissertation.

The purpose of this letter is to request permission for your school's participation in the research portion of the project. The intent of the study is to assess students' understanding of the nature of science after completing a grade 10 science unit which explicitly addresses the nature of science during regular instruction. The students' experience will not diverge from accepted instructional activities; however, the students will benefit from the opportunity to develop their understanding of the nature of science. Information requested from the student will be an open ended response to six questions on the nature of science before and after instruction. Their responses do not count for grades and will take about 20 minutes at the beginning and end of the unit. Additionally, students will be asked to keep a journal and hand it in at the end of the unit. The journal entries provide students an opportunity to reflect on what they have learned and to pose new questions. Journals will be returned to the students and no additional time, outside of normal instruction, will be required.

A representative sample of students will be asked to participate in an interview. The interview process should take about 30 minutes and will take place at school during regular hours. The interviews are used to clarify student responses and identify the sources of the students' views. The interviews will be recorded electronically for transcription and destroyed with the completion of the study. All data is kept strictly confidential, no real names will be used in the reporting of the data and a summary of the results will be available upon request after the study is complete. Informed consent and parental permission will be required for each student. A sample letter of permission is enclosed which will be handed out by the teacher, signed by parents, and returned by the student. Participation in the study is voluntary and your school may withdraw from the study at any time.

Please indicate your consent by forwarding a letter of permission to the address below. Any further information can be obtained by telephoning myself (   ), or the research advisor, Dr. Arthur Stinner (474-9068).

Sincerely,
Don Metz

Appendix C: Parent/Guardian Letter of Permission

Letter of Permission

Dear Parent/Guardian,

In the new Manitoba science curriculum, the understanding of the nature of science is a primary goal. However, it is left to the teacher to provide an appropriate context to achieve this goal. This year, *(teacher)* has agreed to participate in a project which uses the historical development of conceptual models as a context to improve understanding of the nature of science. This program, which is based on the Science 20S chemistry unit, has been developed by Don Metz, a PhD graduate student in the Faculty of Education at the University of Manitoba.

The purpose of this letter is to request permission for your son/daughter's participation in the research portion of the project. The intent of the study is to assess students' understanding of the nature of science after completing a grade 10 science unit which explicitly addresses the nature of science during regular instruction. The students' experience will not diverge from accepted instructional activities; however, the students will benefit from the opportunity to develop their understanding of the nature of science. Information requested from the student will be an open ended response to six questions on the nature of science before and after instruction. Their responses do not count for grades and will take about 20 minutes at the beginning and end of the unit. Additionally, students will be asked to keep a journal and hand it in at the end of the unit. The journal entries provide students an opportunity to reflect on what they have learned and to pose new questions. Journals will be returned to the students, and no additional time, outside of normal instruction, will be required.

A representative sample of students will be asked to participate in an interview. The interview process should take about 30 minutes and will take place at school during regular hours. The interviews are used to clarify student responses and identify the sources of the students' views. The interviews will be recorded electronically for transcription and destroyed with the completion of the study. All data are kept strictly confidential. No real names will be used in the reporting of the data, and a summary of the results will be available upon request after the study is complete. Participation in the study is voluntary and you may withdraw your child (or he or she may also do so) at any time without penalty.

Please indicate your consent by signing in the space below alongside the consent of your son/daughter. Any further information can be obtained by telephoning myself ( ), ( ), or the research advisor, Dr. Arthur Stinner (474-9068).

Sincerely,

Don Metz

Consent Form

Student ___________________________

I grant permission for my son/daughter to participate in the Science 20S research study including (please check):

_______ Pre and post test questionnaire

_______ Journal submission

_______ Interview (if required)

Date __________________________

______________________________ ______________________________

Signature of Parent/Guardian Signature of Student

_____ I wish to receive a copy of the final results (please include name and address)

Appendix D: Teacher's Letter of Permission

Dear (*teacher*)

Thank you for the interest you have expressed concerning your participation in my research. This research project uses the historical development of conceptual models as a context to improve understanding of the nature of science. In the new Manitoba science curriculum, the understanding of the nature of science is a primary goal. However, it is left to the teacher to provide an appropriate context to achieve this goal. This program, which is based on the Science 20S chemistry unit, has been developed by me. I am a PhD graduate student in the Faculty of Education at the University of Manitoba, and this study will provide me with data for my doctoral dissertation.

The purpose of this letter is to request your permission to participate in the research. The intent of the study is to assess students' understanding of the nature of science after completing a grade 10 science unit which explicitly addresses the nature of science during regular instruction. Your role in the study will be to teach the Chemistry 20S unit as prescribed in the outline I have given you. You will have to administer and collect the administrative and parental permission forms, the nature of science journals, and the pre/post tests on the nature of science. I will be asking you to take 10 - 15 minutes each week to provide feedback (by email) to briefly describe your experience in the classroom. Additionally, I will ask that you provide a written evaluation of the unit upon completion of the instruction. Confidentiality is guaranteed if any reference to your responses are published. Participation in the study is voluntary and you may withdraw from the study at any time.

Please indicate your consent by forwarding a letter of permission to the address below. Any further information can be obtained by telephoning myself (   ), (teacher), or the research advisor, Dr. Arthur Stinner (474-9068).

Sincerely, Don Metz

Consent Form

Teacher ________________________

I have reviewed the course outline and the letters of permission for administration and parents. I have also reviewed the attached letter to teachers and I agree to participate in the Science 20S research study.

Date ________________________