THE IMPLICATIONS OF EPISTEMIC DEPENDENCE ON TEACHING THE NATURE OF SCIENCE FOR INTELLECTUAL INDEPENDENCE

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BY

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Abstract

Teaching the nature of science is often justified as a means of increasing students' intellectual independence, critical thinking skills, and scientific literacy. This thesis examines the soundness of these justifications in light of arguments from Hardwig (1985, 1991), Polanyi (1946), and Code (1987) concerning the role of trust in science, the existence of scientific epistemic communities, and the epistemic dependence of laypeople and scientists alike on other scientists.

Various methods for teaching the nature of science are examined in order to see what scientific epistemologies are espoused by them, and whether a means for attaining intellectual independence is provided by them. This analysis illustrates that approaches to teaching the nature of science espouse epistemologies that are based on experimentation and the analysis of evidence and reasons for scientific knowledge. I have concluded that, in many cases, students are not able to analyze the reasons and evidence that support scientific knowledge claims, and complete intellectual independence is often not attainable. The level of independence attainable is often limited to an independent judgement of the degree of certainty of a knowledge claim. That is, while being epistemically dependent on the experts for the reasons that support scientific knowledge claims, students can judge that these knowledge claims are tentative and subject to revision. In this way, a critical disposition towards scientific knowledge,

but not an ability to think critically about the evidence for or against claims to knowledge, is encouraged.

Finally, I address three implications for science education of the fact that laypeople and scientists are epistemically dependent. First, a more accurate scientific epistemology that reflects both knowledge generation and knowledge acquisition needs to be taught. Second, students should be taught to acknowledge their epistemic dependence, and be encouraged and given grounds to trust the products of science. Third, science education should stress scientific ethics, since trust plays such a large role in scientific knowledge generation and acquisition.

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Chapter One

Introduction

Teaching the nature of science is a long standing goal of science education. The justifications for teaching the nature of science include increasing students' intellectual independence, critical thinking skills, and scientific literacy. However, strong arguments from Hardwig (1985, 1991), Polanyi (1946), and Code (1987) concerning the role of trust in science, the existence of scientific epistemic communities, and the epistemic dependence of scientists on their colleagues provide grounds for questioning these justifications for teaching the nature of science. This thesis examines whether the justifications are sound.

I examine various methods for teaching the nature of science in order to see what scientific epistemologies are espoused by them, and whether a means for attaining intellectual independence is provided by them. This analysis concludes that the various approaches to teaching the nature of science espouse epistemologies that are based on experimentation and the analysis of evidence and reasons for scientific knowledge. I have concluded that, in many cases, students are not able to analyze the reasons and evidence that support scientific knowledge claims, and complete intellectual independence is often not attainable. The level of independence attainable is often limited to an independent judgement of the degree of certainty of a knowledge claim. That is, while being epistemically dependent on the experts for the reasons that support scientific knowledge claims, students can judge that these knowledge claims are tentative and subject to revision. In this way, a critical disposition towards scientific knowledge, but not an ability to think critically about the evidence for or against claims to knowledge, is encouraged.

Finally, I address three implications for science education of the fact that laypeople and scientists are epistemically dependent. First, a more accurate scientific epistemology that reflects both knowledge generation and knowledge acquisition needs to be taught. Second, students should be taught to acknowledge their epistemic dependence, and be encouraged and given grounds to trust the products of science. Third, science education should stress scientific ethics, since trust plays such a large role in scientific knowledge generation and acquisition.

Motivation

This study is motivated by the renewed and widespread interest being shown in teaching the nature of science. Recently, instruction in the nature of science has provoked the interest of educators at all levels. In 1989, the First International History and Philosophy of Science and Science Teaching conference was held in Florida. This conference produced 124 papers that were published in six special issues of journals and two books (Gruender & Tobin, 1991). This interest was continued with the Second International History, Philosophy, and Science Teaching Conference held in Kingston, Ontario, in 1992.

In Canada, interest in the goal of teaching the nature of science is evident in other ways. The Science Council of Canada has published seven discussion papers designed to stimulate debate on the goals of school science. Five deal with topics that are discussed in this thesis: Science in Social Issues (Aikenhead, 1980), What is Scientific Thinking? (Munby, 1982), Macroscale: A Holistic Approach to Science Teaching (Risi, 1982), Scientific Literacy: Towards Balance in Setting Goals for School Science Programs (Roberts, 1983), and Epistemology and the Teaching of Science (Nadeau & Désautels, 1984).

In Newfoundland and Labrador, at least two high school science courses include objectives that deal explicitly with the nature of science. Chemistry 2202 devotes unit one to teaching aspects of the nature of science, including discussions on the nature of scientific observation and progress in science. An objective dealing with teaching the nature of science has been added to the Physics 2204 curriculum. Specific indicators of this general objective include students being able to identify acceptable and unacceptable views of science, as well as discuss the role of theories and tentativeness in science. A high school course on science, technology and society is being developed, and is being piloted in Newfoundland and Labrador.

Thus, on international, national, and provincial levels, teaching the nature of science is provoking interest and concern as a goal of science education. With the magnitude of interest being shown in understanding the nature of science as a goal of science education, it is important that the justifications for it are sound.

Outline of the Thesis

There are five subsequent chapters in this thesis. In chapter two, evidence is given for the assertions that teaching the nature of science is a long-standing goal of science teaching, and that it is often justified as a means for increasing students' intellectual independence, critical thinking abilities, and scientific literacy. Students, after instruction in the nature of science, should be able to analyze the evidence and reasons that support scientific knowledge claims so that they can assess the soundness of the claims on their own.

In chapter three, I argue that scientific epistemology must acknowledge the role of testimony and trust in acquiring scientific knowledge. Replication, and the analysis of evidence and reasons, are not always the means of acquiring scientific knowledge by scientists or laypeople.

In chapter four, due to inconsistencies between the contentions of chapters two and three, I conclude that there is a need to examine approaches to teaching the nature of science and the justifications for them based on the promotion of intellectual independence and critical thinking. Three approaches to teaching the nature of science, teaching the history of science, using laboratory activities, and teaching the philosophy of science, are examined. The analysis focuses on the scientific epistemologies that are espoused by each approach, as well as on how each approach purports to encourage intellectual independence and critical thinking skills in students.

In chapter five, expectations about the degree of intellectual independence to be attained from instruction in the nature of science are juxtaposed with the degree of epistemic dependence of scientists and laypeople on other scientists. It is concluded that students may, with instruction in the nature of science, achieve a limited level of independence with respect to judging the degree of certainty of scientific knowledge claims, and acquire a critical disposition toward scientific knowledge. However, complete intellectual independence and the ability to think critically about the evidence for scientific knowledge claims are not attained from instruction in the nature of science.

In chapter six, implications for instruction in the nature of science are addressed. Instruction in the nature of science should acknowledge the role of testimony in scientific knowledge generation and acquisition, and distinguish knowledge acquisition from knowledge generation and justification. Students should be encouraged to acknowledge their own epistemic dependence on scientists, and to trust (rather than to be overly sceptical) the products of scientists. Finally, the need for instruction in scientific ethics is advanced.

Chapter Two

Teaching the Nature of Science and Intellectual Independence

In this chapter, I first will establish that the goal of understanding the nature of science in science education is prevalent among those interested in science education. Three approaches to teaching the nature of science are discussed, and a brief review of some empirical research is given, so that the prevalence of this goal in science education is established. Second, I establish that this goal is justified as a means of increasing students' intellectual independence, critical thinking, scientific literacy, and/or abilities to understand and assess the reasons and evidence for scientific knowledge claims. However, these apparently sound justifications are opposed in the next chapter by claims of inevitable epistemic dependence of others on scientists. In light of these claims, the justifications for teaching the nature of science are called into question.

The Nature of Science as a Goal of Science Education

In this section, I will establish that teaching the nature of science is a long-standing goal of science education. Over the years, this goal consistently has remained as an objective of science curriculum. In recent years, with increasingly complex technological advances and abstract scientific theories, teaching the limits of science and scientists, as well as imparting critical abilities to students, have become foci for science education. These emphases have caused a resurgence of interest in teaching the nature of science. This goal of science education is ingrained in how science courses are taught, and in scientific literature.

In chapter one, an indication of the high level of recent interest in the nature of science as a goal of science education is documented. A review of the literature reveals that this goal was envisioned much earlier. In the late 1800's, Ernst Mach was a strong advocate of students' understanding about science. Matthews (1990) examines Mach's early contribution to science education (which will be examined in chapter three of this thesis) and concludes, "His major educational themes have a great deal of contemporary relevance, particularly as science education strives to see how history and philosophy of science can be best utilized in the classroom and the curricula" (p. 324).

In an extensive review of the research dealing with students' and teachers' conceptions of the nature of science, Lederman (1992) traces the history of this goal in science education. He finds that "concerns for the development of adequate understanding of the nature of science have worn many hats through the years" (p. 332). In 1907, reports of the Central Association of Science and Mathematics Teachers presented strong arguments for increasing the emphasis in science education on the scientific method and the processes of science. In the 1960's, during a period of increased science curriculum development in the post-Sputnik years, the goal of increasing students' understanding of the nature of science was expressed in terms of an emphasis on scientific process and inquiry (Welch, 1979), while, more recently, the goal has been expressed in terms of increasing students' scientific literacy (American

Association for the Advancement of Science, 1989; National Science Teachers Association, 1982).

Thus, increasing students' understanding of the nature of science, by one means or another, has been consistently a goal of science education for over one hundred years. Lederman (1992) notes that, in spite of the lack of consensus on the content taught in science courses,

> there appears to be strong agreement on at least one of the objectives of science instruction. The development of an 'adequate understanding of the nature of science' or an understanding of 'science as a way of knowing' continues to be convincingly advocated as a desired outcome of science instruction. (p. 331)

Methods of Teaching the Nature of Science

The prevalence of the goal of teaching the nature of science is also made evident by the variety of approaches that are employed in teaching it. The use of the history of science, laboratory activities, and the philosophy of science are three such approaches.

One of the earliest approaches for teaching the nature of science is the use of the history of science. In the early 1900's, Mach used the history of science in his teaching and textbooks, such as The history and root of the principle of the conservation of energy (Mach, 1911). This approach has been followed in more recent curriculum developments. A curriculum called "History of Science Cases for High Schools" (Klopfer & Cooley, 1963) was found to increase significantly students' scores on the

Test on Understanding Science (TOUS) (Klopfer & Cooley, 1961), and the history of science has been integrated into many science curricula to date.

Curricula have been developed using the laboratory as a means of increasing students' conceptions of the nature of science. In the early 1960's, curriculum projects such as CHEM Study and Biological Science Curriculum Study (BSCS) focused on promoting inquiry and process skills. Student experimentation in science laboratories has remained a part of science curricula ever since.

A third method that is used to increase students' conceptions of the nature of science is teaching, or implicitly imparting, a philosophy of science. This is done, for the most part, by integrating philosophical statements about science throughout the text or in discussions, and is usually confined to topics such as the scientific method and tentativeness in science. As interest in the goal of increasing students' conceptions of the nature of science increases, perhaps curriculum developers will put more emphasis on this approach. In Newfoundland and Labrador, the Chemistry 2202 course devotes a whole unit solely to philosophical discussions about science. However, the objectives and appendices that cover this unit are in the curriculum guide for teachers; the student textbook for the course does not adequately treat the subject.

Summary of Empirical Research on the Nature of Science

Evidence of interest in the goal of teaching the nature of science has also been reflected in the amount of educational research on this topic. Early studies that attempted to measure students' and teachers' conceptions of the nature of science have reported consistently low scores on instruments developed for this purpose (Anderson, 1950; Carey & Stauss, 1968; Kimball, 1968; Miller, 1963; Schmidt, 1967). Later studies tried to identify some of the misconceptions that students and teachers had about the nature of science. One of the most common findings was the misconception of scientific knowledge as absolute (Aguirre, Haggerty & Linder, 1990; Bady, 1979; Behnke, 1961; Mackay, 1971; Rubba, Horner & Smith, 1981). Misconceptions in other areas were also identified, including those concerning the role of theories in scientific research (Mackay, 1971; Tamir, 1972).

Recent research in this field has yielded some interesting results. It was thought that students' conceptions of the nature of science were inadequate as a result of their teachers' inadequate views. However, recent research is questioning this assumption. This research indicates that teachers' views of the nature of science may not be reflected in what they teach, or the way they teach, and do not correlate with their students' gains in understanding about the nature of science. Brickhouse (1989) found that one out of the three teachers whom she observed engaged in classroom practices that were not consistent with their beliefs. Duschl and Wright (1989) found that the nature of science was not being taught to students due to teachers' perceptions of students needs, and feelings of accountability with respect to teaching the objectives as stated in the curriculum guide. Lederman and Druger (1985) found no relationship between teachers' scores on the Nature of Scientific Knowledge Scale (Rubba, 1977) and their students' mean change in score on the same instrument after a period of instruction. Thus, teachers' conceptions of the nature of science do not translate as often as we might like into their classroom practice, the content of what they teach, or their students' conceptions of the nature of science. However, Zeidler and Lederman (1989) indicated that teachers' language, independently of how accurately it reflected their beliefs about the nature of science, did correlate significantly with their students' scores on the Nature of Scientific Knowledge Scale (Rubba, 1977).

Thus, the amount and prominence of educational research into students' and teachers' conceptions of the nature of science over the last 50 years indicates the value placed on this goal in science education. The low scores of both teachers and students on instruments designed to measure their conceptions, as well as the prevalence of misconceptions in this area, may provide some of the motivation for the current interest in this goal.

Intellectual Independence as a Justification for Teaching the Nature of Science

In the last section, the prevalence of the goal of teaching the nature of science was established. In this section, it will be demonstrated that justifications for teaching the nature of science include the justification of increasing students' intellectual independence with respect to scientific knowledge claims. In chapter four of this thesis, methods for teaching the nature of science will be examined to see whether this justification is sound.

Teaching the nature of science often has been justified in part as a means of fostering intellectual independence. Other ways of expressing this justification for teaching the nature of science include claims of increasing students' scientific literacy, their ability to assess the soundness of scientific knowledge or theories, their critical thinking abilities, or providing a model of a scientific "way of knowing" in which knowledge can be confirmed or verified for oneself.

Munby (1977, March), in describing teaching strategies to promote intellectual independence, defines intellectual independence as follows:

> An individual can be said to be intellectually independent when he has all the resources necessary for judging the truth of a knowledge claim independently of other people... If, for lack [of] one or more of the conditions necessary for Intellectual Independence, an individual is obliged to rely upon someone else's authority, then it is said that the first individual is intellectually dependent upon the second. (p. 6)

Science teachers, he asserts, must:

> analyze teaching to see if means for determining truth are made evident to students in order that they can better assess the truth of statements for themselves... when teaching contains this information it moves decidedly toward providing for Intellectual Independence. (p. 10)

Siegel (1989), defines a critical thinker as a person who is appropriately moved by reasons. In his view, science education can foster critical thinking if it focuses on the philosophy of science:

> Philosophy of science takes as its subject matter a variety of issues and questions relevant to the nature, role, and assessment of reasons in science...Studying philosophy of science, therefore, may contribute powerfully to the understanding of reasons in science, and so to the fostering of critical thinking in science. (p. 30)

Aikenhead (1990), in a similar vein, views a science education that focuses on the reasons supporting scientific knowledge claims as one that fosters intellectual independence. He asserts, "To be intellectually independent is to assess, on one's own, the soundness of the justification proposed for a knowledge claim. Intellectual independence is an explicit goal for science education" (p. 132).

Duschl (1990) distinguishes between teaching scientific knowledge and teaching knowledge about science by writing:

> In a knowledge-about-science curriculum the interactions among science, technology, and society are much more relevant and thus are more easily appreciated. It attempts to stress the most important content, to introduce the guiding conceptions of science, and to establish in learners the ability to evaluate the legitimacy of knowledge claims. (p. 10)

Duschl recognizes the growing complexity of science, and argues that one instructional unit that focuses on the context of discovery should be included in the science curriculum so that students understanding will be enhanced:

> As the processes of science used in gathering and evaluating scientific evidence become more sophisticated, the need to establish a curriculum that examines

> the chain of reasoning that has brought us to this point gains in importance. (1990, p.11)

Gagné (1965) justified teaching the processes of science as a means of increasing a student's ability to understand any scientist's experimental work. After a student has been taught the processes of science

> a scientist should be able to tell this student what he (the scientist) is studying, and the techniques he is using, and what he has found, in a relatively brief fashion, and have the student display a rather profound understanding of it immediately. (p. 5)

Even as the goal of teaching the nature of science was being initiated into science curriculum, Mach (1943) was justifying teaching the history of science as a means of making students more independent:

> A person who has read and understood the Greek and Roman authors has felt and experienced more than one who is restricted to the impressions of the present. He sees how men placed in different circumstances judge quite differently of the same things from what we do to-day. His own judgements will be rendered thus more independent. (p.347)

Many others have justified teaching the nature of science as a means to increasing students' abilities independently to evaluate knowledge claims. The above review provides evidence that this justification is long-standing and well established in educational literature.

Summary

This chapter provides evidence that teaching the nature of science is well established as a goal of science education. Advocates for teaching the nature of science justify it as a means of increasing students' intellectual independence, critical thinking skills, and/or scientific literacy. Students, by understanding how science progresses, how scientists generate scientific knowledge claims, and by analyzing the evidence and reasons that support scientific knowledge claims, are, according to the views espoused in this chapter, better able to evaluate and assess the soundness of scientific knowledge claims that may be made.

This is contrary to the views put forth in the next chapter. It is asserted by several writers that trust, reliance on testimony, and the infrequence of scientific replication are characteristics of science that point to the inability, and even inappropriateness, of teaching students to become intellectually independent. Thus, any justifications for teaching the nature of science as a means of encouraging intellectual independence need to be reevaluated.

Chapter Three

Epistemic Dependence and Trust in Science

We have seen that teaching the nature of science consistently has been a goal of science education, and that it is often justified as a means of increasing students' intellectual independence, critical thinking skills, and abilities to evaluate and assess the soundness of scientific knowledge claims.

These justifications would be called into question, however, if arguments by Hardwig (1985,1991), Code (1987), Harré (1986), Polanyi (1946), and Broad and Wade (1982) are accepted. While each of these writers emphasizes a different aspect of science, the overall theme is one of interdependence among scientists, with scientific knowledge being acquired from other scientists through testimony. Hardwig (1985, 1991) asserts that, as a result of this, all people, including scientists, are inescapably epistemically dependent on others for their knowledge. The implication, Hardwig claims, is that trust in others is involved centrally in science.

Each section of this chapter will examine ways in which scientists more accurately are depicted as being part of a large scientific community, where scientific knowledge is often acquired through testimony and trust, not by replication of experiments or by analysis of reasons and evidence. Chapter four will then examine approaches to teaching the nature of science to see whether the justification of increasing students' intellectual independence is, in fact, realistic, in light of the epistemic interdependence that is necessarily a part of science.

Scientific Ways of Knowing

"Trust", "morals", "ethics", and "values" are words often not used in discussing the acquisition of scientific knowledge claims. More than likely, the words used would include "objective", "proof", "evidence", and "rational". However, in many stages of science, from students learning science from their teachers, to a science specialist reading about a new scientific development in a journal or newspaper, trust is implicit, and the morals, ethics, and values of scientists form the basis of that trust.

Epistemological accounts of the ways of knowing rarely mention the reliance on testimony, and the necessity of trust on the part of the knowledge seeker. Commenting on this point, Code (1987) remarks:

> The knowledge seeker is conceived of as a solitary being: from Plato's insistence upon the incommunicability of knowledge of the Forms, through Descartes' certainty, to Russell's emphasis upon the primacy of knowledge by acquaintance. Not only are human beings taken to be independent in cognitive endeavors, but it is contended that cognitive independence is a desirable condition. The underlying assumption is that even knowledge that might, for one knower, be quite *good* knowledge must inevitably be diluted, denatured, or reduced to opinion when it is conveyed to, or acquired from, another person. Testimony is commonly taken to be of a lesser order of knowledge than knowledge at first hand, and a poor substitute for it. (p.167)

Whether we like it or not, we are often forced to trust someone else's testimony about scientific knowledge. Knowledge acquired through testimony, however, need not be a negative thing. In fact, once the pervasiveness and necessity for knowledge acquired in such a manner is realized, then the role of trust can be put in a more favourable perspective.

Philosophers of science have long argued that evidence and reason form the basis of scientific knowledge; trust usually is not acknowledged as playing a role. Positivistic philosophies of science that rose to prominence as a result of Ernst Mach and the Vienna Circle demanded that only observable phenomena be accepted as scientific knowledge; other less stringent philosophies have required that scientific knowledge be testable or falsifiable using experimental evidence. More recently, in arguing for the rationality of science, in contradiction to Kuhn's (1962) incommensurability-of-theories thesis, Siegel (1989) suggested that scientific method should be regarded as a commitment to evidence. The epistemology of science has always focused on such things as scientific method, formal and informal logic, scientific proof, reasons for theory-choice, and interpreting evidence. In short, descriptions of the ways of knowing in science have focused almost exclusively on the generation and justification of scientific knowledge claims.

Scientists, then, in order to claim to know scientific knowledge claims according to this traditional epistemology, would have to reproduce the experimental work to verify the claim for themselves. Perhaps, scientists could claim to know the knowledge claims by examining other scientists' records of data without performing the actual experiments, by determining what interpretations were made, and by verifying for themselves that the knowledge claims are justified. In both of these ways of knowing, the reasons, evidence and justifications for knowledge claims would have to be analyzed.

But can scientists claim to know a scientific knowledge claim without actually confirming the knowledge claim for themselves? If the answer to this is no, then scientists, in order to claim to know scientific knowledge claims, must verify for themselves each result that they are going to use before pursuing their own interests. Obviously, scientists do not do this, and for good reason: science would never progress if scientists had to start from scratch, verifying each result leading to their own area of inquiry. But it is not just a matter of inadequate time; in using the results of fields outside their own area of expertise "they do not feel called upon, or even competent, to test these results themselves. Scientists must rely heavily for their facts on the authority they acknowledge their fellow scientists to have" (Polanyi & Prosch, 1975).

The second way to know, in which the evidence and reasons for a knowledge claim are analyzed without actually reproducing the actual experiment, poses similar problems. Scientists could never know all the evidence and reasons for all previous knowledge claims. Much of the evidence would be outside of their area of expertise, and they would not be capable, in all cases, of understanding what counts as good reasons or of interpreting the data of various instruments. Hardwig (1985) argues that in these situations it is irrational to think for oneself: "rationality sometimes consists in deferring to epistemic authority" (p. 343), since "if I were to pursue epistemic autonomy across the board, I would succeed only in holding relatively uninformed, unreliable, crude, untested, and therefore *irrational* beliefs" (p. 340). The magnitude of knowledge that would need to be verified or analyzed before the individual could claim to know is prohibitive. Scientists have neither the time nor the competence to verify or analyze the evidence and reasons for all scientific knowledge claims.

The Education of a Scientist

So how do prospective scientists learn their science? Are all the experiments that form the foundation of our scientific knowledge to be performed by students before they accept the knowledge as confirmed? Are they to be critical of all new knowledge taught them? Polanyi (1946) describes the process by which apprentice scientists gain scientific knowledge and practical experience from their teachers. These beginning scientists must trust their teachers and learn the premises of science by submitting to their teachers' authority:

> At every stage of his progress towards this end he is urged on by the belief that certain things as yet beyond his knowledge and even understanding are on the whole true and valuable, so that it is worth spending his most intensive efforts on mastering them. This represents a recognition of the authority of that which he is going to learn and of those from whom he is going to learn it. (p. 45)

Kuhn has written about the necessity of a certain amount of dogmatism in science education. In order to solve the puzzles posed by normal science, scientists must accept without question certain fundamental beliefs of current scientific paradigms. Working within the confines of the existing paradigms, normal scientists do research to expand the amount and depth of scientific knowledge that can be generated by the paradigms. As more research is done using these paradigms, anomalies, or experimental results, that do not support the paradigms arise. When these anomalies accumulate to the extent that they no longer can be ignored, a crisis period ensues, and science enters a period of revolution. New paradigms are proposed that may have different underlying assumptions than the old paradigm, and may be incommensurable in that they cannot be compared in a neutral way. Once the new paradigms are accepted, a new period of normal science ensues, in which, once again, the underlying assumptions are unquestioned by normal scientists, and new scientific knowledge is generated. It is up to the teacher, Kuhn has written, to prepare students to become normal scientists, uncritical of the existing paradigm, in order to increase the amount of scientific knowledge that can be generated by the existing paradigms.

Norris (1990) argues that students have no access to direct evidence for many propositions that they are taught. Instead of questioning the actual reasons and evidence for the propositions, he suggests that the students analyze the grounds for their belief in the propositions. If their belief is grounded in the recognition of experts, like the author of a chemistry textbook, then the belief can constitute a rational trust. Norris asserts: "if college students are not willing to rationally trust, then I am not sure how they can get by in the world" (p. 238).

Thus, there are many scientific knowledge claims that students must accept on the basis of authority. They have neither the means nor the ability to analyze or understand the evidence or reasons for many scientific knowledge claims. They are expected to trust their teachers and textbooks, and learn the underlying assumptions, methodology, and standards of the current paradigms.

Teamwork in Science

It is not just the magnitude of scientific knowledge being generated that makes it impossible for one person to verify all of it. Much scientific research takes years to complete, and employs teams of scientists. Hardwig (1985) reports on one such research project that determined the lifetime of charm particles. The equipment needed to do the experiment took 50 person/years to construct; the actual data collection, which involved 50 physicists, took another 50 person/years; and one of the five groups doing the analysis of the data took 60 person/years and 40 physicists to complete their part of the analysis. Every person involved had their own special role in the project; not one person knew all the evidence or rationale for the whole project; not one could do all the analysis. It would be impossible for one person to verify the findings of the research.

A survey of every tenth volume since 1930 of the periodical Nature shows that the average number of authors per article has increased dramatically, and has increased faster in recent decades. In 1930, the average number of authors per articles was 1.2; by 1990 it had more than tripled to 4.1. The survey also shows that the average number of countries represented per article increased by 5% from 1930 to 1980; in the next ten years it increased by 14% (Norris & Griffiths, 1992, May). Increasingly, research is being done using teams of scientists instead of individuals, and the time and the expertise necessary to complete such projects prohibits their being done by individuals. Thus, such research is not only not being reproduced, the total evidence, rationale, analysis, and interpretation is not known (or knowable) by one individual. Scientists must trust their colleagues working on the same project, since their science backgrounds, technical expertise, and duration of their lives do not permit them to verify all the findings for themselves. If a scientist betrays that trust, horror sweeps through the scientific community: "each researcher is forced to acknowledge the extent to which his own work rests on the work of others -- work which he has not and could not (if only for reasons of time and expense) verify for himself" (Hardwig, 1985, p. 348).

Originality in Science

Another factor that inhibits scientific knowledge from being replicated or verified by an individual is the value placed on originality in science. Hardwig (1991) asserts that "the structure of modern science acts to prevent replication, not to ensure it. It is virtually impossible to obtain funding for attempts to replicate the work of others, and academic credit normally is given only for new findings" (p. 703). Thus, scientists are not encouraged, financially or academically, to replicate the works of other scientists, and many experiments are never verified or replicated because of this. Scientists accept these scientific knowledge claims by relying on the testimony of other scientists, not because they have actually verified the results for themselves. They must trust that the scientists have published the results honestly and without distorting or inventing data.

This is not to say that scientific experiments are never replicated. Some are. It is also not to say that replication is the only means of discovering errors. Sometimes, errors are discovered indirectly when the consequences of experimental results lead to contradictions.

The Self-Policing of Science

The three mechanisms that make up the self-policing system of science, according to Broad and Wade (1982), are peer review, the referee system, and replication. Peer review refers to the process of evaluation by committees of scientists, who are responsible for deciding which research grant applications should be awarded funding. "The committee members are meant to read each application with great care, rating each according to its scientific merits. This process is the first stage at which any fraudulent research proposal might be caught" (Broad & Wade, 1982, p. 62).

The second mechanism, the referee system, comes into effect when a paper has been submitted for publication in a scientific journal. At this stage, the editor of the journal will send the paper to other scientists working within the same field so that they will referee the paper, and

> advise the editor as to whether the work is new, whether it properly acknowledges the other researchers on whose results it depends, and most

importantly, whether the right methods have been used in conducting the experiment and the right arguments in discussing the results. (Broad and Wade, 1982, p. 17)

These referees do not replicate the experiment; they judge its merit according to the above criteria. Thus, the results are not verified or confirmed in the refereeing process; the referees trust that those submitting papers for publication have not tried to distort the results or to invent data to support their hypotheses.

The third mechanism, replication, deals with the way that other scientists, upon reading a paper published in a journal, can try to replicate the results by performing similar experiments. Experiments must be described in such a manner so as to make replication possible so that, as Broad and Wade (1982) assert, "any fraudulent experiment, so established wisdom goes, is liable to be shown up when others try to replicate it" (p. 62). For reasons described earlier, experiments are not replicated as a rule. Broad and Wade (1982) describe numerous scientists who have been caught trying to publish fraudulent or plagiarized results. In most of the cases, neither of the three policing mechanisms were successful in detecting the fraud. Instead, in most cases, the fraud was detected by a person working closely with the scientist who had access to information or data that the reviewers or other scientists did not. Even in cases where replication was attempted and failed, the fraud was still not identified as such, since those attempting replication felt that they were not performing a technique properly or that the scientist who had published the paper had more skill.

Thus, the so called "self-policing" of science seems to be based more on trust than on replication: editors, reviewers, and fellow scientists must trust that those making the scientific knowledge claims performed their experiments as they have recorded them, got the results that they claim, and analyzed all the data, not just the data that supported their hypotheses. They must trust these scientists because they usually do not, for reasons of expertise, time, and money, verify the results for themselves.

Epistemic Dependence

It appears that scientists, in almost every phase of their education and professional careers, must trust their teachers and fellow scientists since they have neither the expertise, time, nor money to verify all the scientific knowledge claims that they claim to know and depend on to do their research. While there is much in science for which they do know the evidence and reasons, there is a lot that they have not verified personally, and much knowledge for which they do not know the evidence or reasons.

Hardwig (1985) claims that laypeople and scientists alike are epistemically dependent on the scientific community. Submitting to this dependence, he asserts, is often more rational than trying to determine the evidence for oneself. He argues that people may claim to know propositions without being able to understand the reasons or evidence that support them, if they believe that experts have good reasons for believing the propositions. Increasingly, experiments are being performed with large teams of scientists from different fields of expertise, so that no one scientist knows all the reasons or evidence for the result. Each scientist in that team is epistemically dependent on the others working on the same project.

Epistemic individualists, if there ever were such people, are being replaced by epistemic communities, where everyone in that community relies on others for their knowledge. Code (1987) argues that epistemic individualism is a fallacy:

> Early childhood knowledge acquisition gives some indication of the scope of cognitive interdependence, and it would be a mistake to think that interdependence ends with childhood, that mature cognitive agents are recognizable by achieved autonomy. Childhood teaches us how to be interdependent. To entertain the illusion that, in adulthood, one leaves this interdependence entirely behind is to discount much of one's everyday cognitive experience. (p. 169)

Rom Harré (1986) writes specifically about the shared knowledge in a scientific community. In fact, the title of the first chapter in Varieties of Realism (1986) is "Science as a Communal Practice". In recognizing the dependence of laypeople and scientists on the work of other scientists, Harré (1986) refers several times to the need for a moral order or a code of ethics that must be followed by scientists practising in the scientific community. Since "scientific knowledge, is itself defined in moral terms... It is that knowledge upon which one can rely" (Harré, p. 13), the scientific community must adhere to a strict moral code. Failing to adhere to this moral order will result in the trustworthiness of the scientific community being called into question. "The practical reliability of scientific knowledge is required to sustain its moral quality" (Harré, p.13). Thus, perceiving science as a communal practice, with scientists being dependent upon other scientists for their knowledge, imparts a totally different perspective on scientific knowledge, with the emphasis being on how trustworthy or reliable the scientific knowledge claim is. However, if science is perceived as an individual endeavour, with all knowledge claims being verified before being accepted, science is perceived as being much more rational and objective, with no need for the terms "morality" and "reliability".

Polanyi, in his description of the apprenticeship of young scientists and of the other ways in which the scientific community exhibits mutual reliance among its members, depicts the scientific conscience that must pervade all the members of the scientific community. Scientists must subscribe to the premises of science "by an act of devotion" (1946, p. 54) so that the tradition of science will be upheld. "It is a spiritual reality which stands over them and compels their allegiance" (1946, p. 54), so that "the scientist normally performs his emotional and moral surrender to science" (1946, p. 55). Thus scientists, when exercising their authority over their fellow scientists and laypeople, must act in a moral and responsible way so that they, and their products, the scientific knowledge claims, can be trusted.

Summary

In this chapter I have attempted to portray the many areas of science in which trust and a reliance on testimony are an integral part. Expensive instruments, highly specialized experts, teams of scientists working on international science projects, human mortality and the sheer magnitude of the scientific knowledge being generated are all factors that decrease the likelihood of replication of scientific experiments. The ability to understand or assess the reasons and evidence for scientific knowledge claims today appears to be beyond the reach of all but the most specialized of scientists in a particular field. Scientists and laypeople alike are often epistemically dependent on other scientists.

Scientists, then, often acquire scientific knowledge without understanding the reasons or evidence that support it, and without confirming such knowledge for themselves. Science students, however, are to be encouraged to attain intellectual independence by being able to assess the soundness of scientific knowledge claims when they are often incapable of understanding the evidence and reasons for them. Educators that advocate intellectual independence as a goal of science education are not only giving students an unrealistic view of their abilities, and perhaps discouraging them from a career in science by putting undue pressure on them, they are also portraying a picture of scientists as excessively rational, analytical, and omnipotent.

The next chapter looks at approaches to teaching the nature of science to see the means by which various degrees of intellectual independence are espoused as being attainable. Subsequently, these expectations of the degrees of intellectual independence attainable are juxtaposed with the reality of epistemic dependence to determine if some level of intellectual independence is possible.

Chapter Four

Approaches for Teaching the Nature of Science and the Attainment of Intellectual Independence

I have demonstrated that increasing students' understanding of the nature of science is a long standing goal of science education, and that it is often justified as a means of increasing students' intellectual independence and critical thinking abilities. However, I have also shown that trust plays a major role in the acquisition of scientific knowledge for both scientists and laypeople, and that scientists and laypeople alike are inescapably epistemically dependent on other scientists. Examination of the approaches to teaching the nature of science is warranted, it seems, for two reasons. First, the examination should inquire into how scientists are portrayed as acquiring scientific knowledge. Portraying scientists as guided only by reasons, evidence, and experimental results would give an inaccurate view of how much of their scientific knowledge is acquired. Second, the examination should inquire into how increasing students' knowledge of the nature of science is to lead to their intellectual independence. Three approaches are used to teach the nature of science, namely, that of using the history of science, labwork, and the philosophy of science. All will be examined to see if they offer any particular advantage for achieving this educational goal.

There is some overlap between these three approaches. For example, there is an inherent philosophy of science that is conveyed in using particular laboratory approaches such as discovery learning. As well, separate analysis is not meant to imply that teachers or curricula use only one approach exclusively; many teachers and curricula use more than one when teaching about the nature of science. These three approaches do, however, offer different perspectives on the nature of science and strategies for increasing intellectual independence.

The History of Science

The means and justifications for teaching the history of science are varied. Because of this, general statements about the consequences of teaching the history of science are not possible without subdividing this section further. A review of articles and curricula that emphasize this goal reveals three ways that the history of science is conveyed to students. The first method involves simply listing names of inventors or scientists with their corresponding discoveries or contributions to science. The second method includes the information given using the first method, but also includes details of the experimental work done, observations made, and interpretations made that resulted in the scientific contributions. The third method subsumes the second, but also includes personal, economic, and sociological information that is pertinent to the discovery.

Names, Dates, and Discoveries

This method of teaching the history of science is the least inclusive of all the methods; it involves providing only the barest of details about scientific discoveries.

Typically, only the scientists' names, the discoveries that were made, and perhaps the dates of the discoveries are provided. No details about how the discoveries were made or confirmed are provided, much less any particular sociological or personal details.

Many science textbooks use this approach, as well as more inclusive approaches, for teaching some concepts. BSCS Biology (1968) lists the history of biological concepts as its second theme in the forward of the second edition. However, the text's use of the history of science is not as prevalent as the forward suggests. Looking through the text for historical material to see what aspects of the nature of science are portrayed leaves the impression that the history of science is not a major theme, but a minor inclusion. The first four chapters include only one historical account, and it is typical of the approach being discussed. The results of Thomas Malthus' studies on population are given, without descriptions of experimental work or methods. Other excerpts from the history of science are given in subsequent chapters. For the most part, these are brief, chronologically ordered descriptions of when certain organisms where first observed or principles developed. Many of the experimental details are omitted, as well as other related details that would give a fuller picture of what science is really like. This is not to say that BSCS Biology uses exclusively this approach to the history of science; a more comprehensive historical account of experimental work is in the chapter on heredity, where the experimental works of Mendel, Sutton, and Morgan are described. However, for the most part, the evidence and reasons that scientists had for their scientific knowledge claims are not given; students are not given any information that would help them evaluate the claims.

This approach to teaching the history of science is quite common in science textbooks. Other, more inclusive, approaches may degenerate into this approach if teachers feels they don't have enough time to cover what may be considered extra material or frills. If this is the only method used to teach the nature of science, then students will not be taught how science progresses, how scientists make decisions or interpretations, or how trust plays a role in science. Students may perceive scientific knowledge as growing and changing without understanding how or why, and thus may be sceptical of scientific knowledge claims, hold them tentatively, but be unable to assess by themselves the soundness of the knowledge claims. This approach to teaching the history of science puts students in the greatest position of epistemic dependence on their teachers and textbooks.

Names, Dates, and Experimental Details

Using this approach to teaching the history of science, the experimental details that support the scientific knowledge claims are given. This approach currently is gaining prominence as a means of promoting conceptual change in students. Students often hold misconceptions about science that are very similar to earlier scientific beliefs. By describing to the students experiments that show how newer conceptions are more accurate and acceptable, students are more likely to adopt the currently accepted scientific theory than hold to the older outdated version.

An early champion of this approach was Ernst Mach. His approach to science teaching is described by Matthews (1990):

> Aim for understanding and comprehension of the subject matter; teach a little, but teach it well; follow the historical order of development of a subject...by teaching science, teach about science; show that just as individual ideas can be improved, so also scientific ideas have constantly been, and will continue to be, overhauled and improved..." (1990, p. 320)

Matthews goes on to describe three reasons for Mach's use of the historical approach to teaching science. First, the historical approach encourages understanding of scientific concepts: "He believed in a vague form of the recapitulation thesis later popularized by Piaget: that children's intellectual growth closely follows that of the development of science" (1990, p. 321). Second, Mach felt that the historical approach emphasizes the fallibility of science, and as such should prevent scientism. Matthews quotes Mach: "Whoever knows only one view or one form of a view does not believe that another has ever stood in its place, or that another will ever succeed it; he neither doubts nor tests" (Mach, 1911, p. 17). Thus students were meant to be sceptical of all scientific knowledge claims, and intellectual independence was encouraged: "Recognizing the historicity of all cognition promoted independence of mind, a cardinal virtue for Mach" (Matthews, 1990, p.321). Third, Mach thought that the historical method of teaching science would show students how science is to be conducted, and provide a model for them to follow in their own inquiries.

Although Mach's ideas are more than one hundred years old, many educators still find them relevant today. Duschl, for one, seems to advocate this method of science teaching for very similar reasons. Without clarification or explicit instruction, however, an incomplete picture of science and epistemology of science is portrayed. By teaching a few concepts in great detail, showing how they were developed, expanded and refined by the various contributing scientists, students may perceive that scientists replicate or analyze the evidence and reasons for all scientific knowledge claims throughout history. This method, with its focus on understanding the reasons and evidence for scientific knowledge claims throughout history, suggests that not only must students be able to understand current knowledge claims, they must also be able to understand all the evidence and reasons for past knowledge claims, and why they were inadequate compared to the current theories. The burden placed on the student (and the teacher) is tremendous.

This method, by focusing only on the experimental details and omitting personal and sociological factors, portrays science as an extremely rational enterprise. By showing the inadequacies of past theories and the supporting evidence for current theories (the method of promoting conceptual change), this approach may not promote a tentative view towards current scientific knowledge claims. That is, students may come to understand that past theories were tentative, but, by spending so much time and effort convincing them of the validity of current theories, may be much more likely to believe them as being true for all time. More to the point of this thesis, this method promotes the view that scientists, and students if they are to understand science, must understand the reasons and evidence for past and current scientific theories. It does not address their epistemic dependence on scientists with respect to the vast amount of scientific knowledge being generated, for which they will have neither the time nor the expertise to learn and understand all the supporting evidence and reasons.

Names, Dates, Discoveries; and Experimental, Personal, and Sociological Details

Teaching a history of science that includes names, dates, discoveries, as well as experimental, personal, and sociological details is becoming increasingly popular. However, the method is not new. Teaching the more inclusive perspective on the history of science was the goal of James Conant. His book On understanding science (1947) reiterated many of the ideas of Mach concerning teaching the history of science. Conant wrote that laypersons should be made aware of the "tactics and strategies of science" (Conant, 1947, p. 16). Conant opposed what he took to be typical of philosophies of the time, which espoused a view that "the scientific method is marked by the following features: (a) careful and accurate classification of facts and observation of their correlation and sequence..." (Pearson, 1911, p. 37). Conant instead proposed that "the stumbling way in which even the ablest of the early scientists had to fight through thickets of erroneous observation, misleading generalizations, inadequate formulations, and unconscious prejudice is the story which seems to me needs telling" (Conant, 1947, p. 15). In Conant's view, science philosophies current in his day did not portray an accurate picture of the scientific enterprise; a more accurate picture could be seen by studying the history of science, including as much as possible the social climate, personal conflicts and competition, and difficulties involved in theory transition.

A central theme in his teaching was the evolution of new conceptual schemes. Conant constantly reminds the reader that what seems so obvious now was not always so obvious. This is an important element in students' understanding the rationality of past scientists:

> What most of us today regard as a fact, namely, that the earth is surrounded by a sea of air that exerts pressure, was in the 1640's a new conceptual scheme that had still to weather a series of experimental tests before it would be generally adopted. (Conant & Nash, 1964, p. 6)

Conant helps students see how scientists could hold the beliefs they did so strongly, even in the face of evidence to the contrary. He starts the story of Torricelli's experimental work with some philosophical advice:

> Let us remember that the conceptual scheme implied by the phrase 'nature abhors a vacuum' was by no means the nonsense we sometimes imply today. In a limited way this idea explained adequately a number of apparently unrelated phenomena and that is one of the tests of any conceptual scheme. (Conant, 1947, 36)

Statements like these are abundant throughout his text. Also prevalent in his case studies is a great deal of original material by scientists. These illustrate working hypotheses, details on laboratory setups, observations obtained, and inferences made. They also include the stops and starts, the changing of equipment when results were not forthcoming, and the speculations and expectations that preceded the observations.

Another inclusion in his case studies is a Science and Society section, in which relevant historical material is related to the scientist's work.

Conant's case studies appear to convey to students several aspects of the scientific enterprise. Analyses that involve philosophical, as well as sociological, economic, and personal factors are included, as well as descriptions both of theory development and justification. Throughout the text runs a strong central theme of tentativeness in science.

Another well-known advocate of teaching a comprehensive history of science is Gerald Holton, one of the directors of the high school physics curriculum Harvard Project Physics (Holton, Rutherford & Watson, 1968). Holton thought that in historical accounts of science nine dimensions should be addressed for a complete understanding of a scientific event. Acknowledging some overlap between dimensions, he describes them as such:

1. The awareness of public scientific knowledge at the time of a scientific event.
2. A time trajectory of the state of public scientific knowledge that leads up to and goes beyond the scientific event. Included would be parallel developments, continuities and discontinuities, and the tracing of public opinion.
3. The reconstruction of the personal aspect of the scientific event. Letters, drafts, laboratory notebooks, interviews and the like would be studied.
4. A time trajectory of the private scientific activity under study.
5. The psychobiographical development of the scientist.
6. A line that traces the ideological or political as well as literary events and relates them to the other trajectories.

7. The sociological setting, conditions, influences that arise from, for example, the dynamics of team work, the link between science and public policy, or institutional channels for the funding, evaluation, and acceptance of scientific work.
8. The analysis of the epistemological and logical structure of the work under study.
9. The individual scientist's thematic presuppositions that motivate his research. (Holton, 1988)

Holton intended to incorporate these dimensions in Harvard Project Physics. Instead of teaching unconnected scientific concepts, Holton wanted to show the links that could be made between science and other areas like philosophy, political science, literature and arts:

> One can thereby hope to develop a sequence of organically related ideas whose pursuit takes on an ever higher vantage point, a more encompassing view of the working nature, of the style of life of the scientist, and of the power of the human mind. (Holton, 1976, p. 334)

Many excerpts from Harvard Project Physics tell a detailed story of scientific developments. However, like BSCS Biology (Green Version, 1968), the detail is not maintained uniformly throughout. At times, only the names, dates and discoveries are given, and students must accept the results without questioning, since without the evidence or details of the experiment they have no grounds for judging the results. In other cases, the experimental evidence is described, and shown to falsify a theory, yet due to external factors (loyalty to another scientist, disbelief of evidence, questioning the credibility of a scientist) the evidence is not accepted as falsifying the theory.

Two examples illustrate these two extremes. In discussing the falsification of Newton's corpuscular theory of light, the text shows how the two theories of light, the wave theory and the corpuscular theory, offer contradictory predictions about the relative speed of light through water and air.

> You might think that it would be fairly easy to devise an experiment to determine which prediction is correct. All one has to do is measure the speed of light in water... Not until the middle of the nineteenth century did Fizeau and Foucault measure the speed of light in water. The results agreed with the predictions of the wave model: the speed of light is lower in water than in air... The Foucault-Fizeau experiments of 1850 were generally regarded as driving the last nail in the coffin of the particle theory. (Holton, Rutherford, & Watson, 1968, p.12-13)

This illustrates a situation where content is taught by providing only the experimental result without any description of the experimental setup or the data that support the result. Only one of Holton's nine dimensions is visible: a time trajectory of public scientific activity is sketched throughout the section.

The section that follows the statement of Foucault-Fizeau's results provides a sharp contrast to the authoritative prose. In a description of the work of Thomas Young, an excellent job is done to include as many of Holton's nine dimensions, and to show a segment of science's history in an interesting and accurate way. Young's double-slit experiment is described in suitable detail for the students to understand. In the margin there is a picture of Young, along with a brief synopsis of his interests and occupations.

Pictures of his original drawings are given, along with direct quotes from an original paper. What follows conveys without doubt how experimental evidence is sometimes received by the scientific community and society:

> Young was received with ridicule and even hostility by those British scientists to whom Newton's name was sacred. It was not until 1818, when the French physicist Augustin Fresnel proposed a mathematical wave theory of his own, that Young's research got the credit it deserved. (Holton, et al., 1968, p. 14)

To further illustrate the rejection of Young's work, a negative review from the Edinburgh Review is included, which states "this paper... is in fact destitute of every species of merit" (Holton, et al., 1968, p. 14). In this excerpt a detailed picture of how scientific evidence may be rejected or ignored is imparted, and scientists are seen as not being the objective, prejudice-free people they are often purported to be.

Conant's and Holton's works illustrate this third approach to teaching the history of science. Scientific discoveries seem to be analyzed on every dimension, with the implication that to understand scientific discoveries and scientific theory change, a full picture that includes not only the experimental details but also personal, economic, and social details, is necessary. Using this approach, the students must replicate some past experiments to confirm them first hand. For many of the experiments that are not replicated, the experimental evidence and reasons for scientific knowledge claims are given for the students to assess. As well, students must judge the source of the scientific knowledge claim by analyzing personal, social and economic conditions. The burden of analysis becomes heavier for the student (and, again, the teacher).

While this type of exposition is very interesting and entertaining to read, using this method to analyze current or future scientific discoveries often will prove fruitless for students. The level of expertise required for critically analyzing today's scientific discoveries, as well as the insight necessary to evaluate social and economic conditions, is much too high for students, and many scientists as well, to be able to assess properly. Thus, while students may have a detailed account of past, basic discoveries, they likely do not have the means to judge current or future discoveries in the same way.

The use of a more complete history of science, one that includes personal, sociological and economic details, does seem to be the best method to show the role of trust in science. In Conant and Nash's (1964) and Holton's (1978) case studies this message was, to a large extent, implicit. Historical descriptions of past scientific discoveries that deal explicitly with the role of trust in the acceptance of scientific ideas would serve to illustrate the point even more; perhaps even descriptions of the way that scientists who betrayed that trust to further their scientific careers would illustrate the prevalence and necessity of trust in the scientific community, and the need for strict ethics in science.

Summary

Of the three methods of teaching the history of science outlined, the third method seems to portray the most complete picture of the scientific enterprise and seems to hold the most promise for portraying the role of trust in science. It also may be the method most effective in promoting a good understanding of scientific knowledge claims and reasons for past theory change. It aims for a complete analysis of past scientific knowledge claims, as well as a basis for holding tentatively future knowledge claims by portraying the humanistic side of science. However, as a general method of analyzing and assessing the soundness of knowledge claims, which is necessary in promoting intellectual independence and critical thinking, the third method is doomed to fail. The time, equipment, expertise, as well as the personal, economic and social details, that would be needed to analyze most current and future scientific knowledge claims in the same manner are beyond the reach of students, and for that matter, most scientists as well. In this respect, the students are in the position to know only the discovery and date of any future knowledge claim, and perhaps the name of the chief or main scientist working on the team that made the discovery. They are in a position of epistemic dependence. Without the means to judge the scientific knowledge claim or the scientists that made it, they will be able only to be sceptical of a scientific process that they have been told is open to human error and interpretation, and believe the products of science to be tentative. However, they will have no means to question the actual knowledge claim on a rational basis.

Laboratory Approaches

A second method that is often employed in science education to convey an understanding of the nature of science is the use of laboratory activities, experiments, or demonstrations in which students "behave like scientists". These are used to impart a wide range of perspectives about the nature of science: learning a scientific method, learning how scientists make discoveries or reach conclusions, and learning the epistemological status of scientific knowledge claims. The underlying assumption is that the best way to show what science is like is to do it. Sometimes the lab activities are designed specifically to convey an aspect of the nature of science; other times different objectives, like skill or content acquisition, are emphasized. Nevertheless, many students may feel that the activities that they do in the laboratory accurately represent the way science is done, whether that is the intention or not.

In this section, general approaches to laboratory work that are used to convey an aspect of the nature of science will be analyzed to see whether they impart a particular epistemology of science, and whether that epistemology acknowledges the role of trust in science. As well, the laboratory approaches will be examined to see whether a means for achieving intellectual independence is available. Common approaches to laboratory work in school include inquiry, discovery learning, science fairs or projects, a process approach, and constructivist-motivated laboratories. These will be described and examined in this section. Laboratory approaches that will not be discussed in this section are experiments that demonstrate, confirm, or test theories.

Inquiry

Joseph Schwab is largely responsible for coining the phrase "science as inquiry", or, as he prefers, "enquiry". He criticizes science textbooks that portray science as a set of collected facts, or, in his terms, as a "rhetoric of conclusions" (Schwab, 1964, p. 24). Instead, Schwab asserts that science should be taught

> as a product of fluid enquiry; [the public should] understand that it is a mode of investigation which rests on conceptual innovation, proceeds through uncertainty and failure, and eventuates in knowledge whch [sic] is contingent, dubitable, and hard to come by. (p. 5)

Schwab postulates a distinction between stable and fluid enquiry in a manner roughly equivalent to Kuhn's (1962) distinction between normal and revolutionary science. He argues that science has always been taught as a stable inquiry, where current theories and principles are taught, and research is seen to involve using these theories and principles "to fill a particular blank space in the growing body of knowledge" (1964, p. 16). This type of education does not answer the current needs of society, he argues, since scientific growth involves questioning these basic theories and principles, and the invention of new conceptions. This type of activity is fluid inquiry; it is typified by subject matter being redefined by new principles that guide the next phase of stable inquiry. Schwab calls this the revisionary character of scientific knowledge, and maintains that science should be taught as involving refinements of current principles or theories (stable inquiry) as well as the complete revision or replacement of them (fluid inquiry).

Schwab's goal in teaching science as an inquiry is to convey to students the appropriate manner in which to hold the massive amount of knowledge being generated. He asserts that the rate of revision in science has accelerated in recent years to the extent that scientific knowledge is quickly becoming outdated. If students do not understand the methods of stable and fluid inquiry, and their resulting products and revisions of knowledge, confidence in science will diminish:

> Unprepared for such a change [in scientific knowledge] and unaware of what produced it, the former student can do no better than to doubt the soundness of his textbooks and his teachers. In a great many cases, this doubt of teacher and textbook becomes a doubt of science itself, and of professional competence in general. The former student has no recourse but to fall into a dangerous relativism or cynicism. (Schwab, 1963, p.45.)

Connelly, Finegold, Clipsham and Wahlstrom (1977) reiterate this view in their book Scientific Enquiry and the Teaching of Science:

> The ultimate goal is to develop the student's power and freedom with respect to scientific knowledge - that is, to develop in him the intellectual capacity to inform himself about a field of enquiry such as chemistry or physics. In this way he becomes independent of the teacher and of the curriculum, ultimately free of these two constraints in his education... The basic concern is to

> encourage the intellectual independence of students with respect to scientific knowledge claims. (p. 7)

Thus by teaching science as an inquiry, that is, emphasizing the human creativity and interpretation that is used to generate scientific knowledge claims and thus the tentative nature of the products of science, intellectual independence will be encouraged. Students, by judging appropriately scientific knowledge claims as tentative, will not question the rationality of scientists and the scientific process when changes occur, because they will understand how scientific knowledge is generated and will expect revisions or changes.

Schwab's inquiry approach to laboratory work is illustrated to a small degree in BSCS (green version) High School Biology (1963), of which Schwab was the editor, and to a much larger extent in his "Invitations to Enquiry" (Schwab, 1963) (supplementary activities that were designed by Schwab for the BSCS texts). The laboratory activities in BSCS green version (1963) are intended to show models of inquiry by showing how the laboratory can be used to generate scientific knowledge claims. The main focus seems to be on content acquisition with inquiry as a minor focus:

> Many of the exercises are of the traditional kind, serving the necessary traditional purpose of making clear and vivid materials expounded by the text. But many are of another kind. They are not illustrative but investigatory. They treat problems for which the text does not provide answers. They create situations in which the student may participate in the enquiry. (Schwab, 1963, p. 40)

It seems clear from this statement that Schwab intends these investigatory activities to mirror the work of scientists. As such, laboratory work was to precede classroom instruction, or concern itself with subject areas not covered in the classroom, so that students would be able to conduct their own program of inquiry with varying degrees of openness and permissiveness. Three levels of openness are described, with activities in which the given information ranges from problems and proposed means to solve them but no answers; to problems with neither means nor answers; to situations where students must find their own problems, means and answers.

High School Biology (BSCS green version, 1968), for the most part, gave the background information, purpose, and procedure of the investigations, leaving the student to perform the lab and interpret the data by answering leading questions. This approach to teaching science as an inquiry amounts to displaying only the variety of ways that the data is obtained and interpreted in a laboratory, and places less emphasis on the students' ability to formulate their own problems and procedures. The answers to some of the problems being investigated are given to the students, not in the lab manual, but in the textbook, so that "the appearance, but not the reality, of enquiry is provided" (Schwab, 1964, p.55).

In Schwab's (1963) "Invitations to Enquiry" students get a more in-depth look at the process of inquiry itself. Instead of inquiring to gain scientific knowledge through the use of the lab, students are given information about scientist's attempts at inquiry, and are asked to analyze, in depth, various aspects of the process to see the logical foundations of the hypotheses, the way they are tested, the way that the conceptions of the scientists affect the interpretations, and the different types of experimental error. Thus, while the actual investigatory laboratory work is meant to imitate scientific inquiry, the Invitations to Enquiry are inquiries into inquiry. These invitations emphasize the reasons why scientific knowledge is tentative by showing the assumptions, inferences, and errors that are made in the inquiry process.

If these invitations were discussed and debated in class, (as supplementary material, it may be overlooked) students would get a very good view of the interpretive nature of scientific knowledge claims, and would no doubt hold scientific knowledge claims with a high degree of tentativeness. Students would also practice analyzing reasons for making decisions, since the invitations provide a very structured, critical, analytical look at scientific investigations, and, as such, illustrate a model of rationality that the students can use. Starr (1972) has provided evidence that students who used these invitations did improve their critical thinking skills more than students who followed the regular BSCS High School Biology textbook.

Inquiry, then, with its heavy emphasis on the analysis of the scientific process of generating and justifying knowledge claims, attempts to encourage intellectual independence and critical thinking in two ways. First, it deals extensively with the process of generating scientific knowledge claims, and provides models of scientific work so that students will be able to inquire into problems of their own. Second, by focusing on the process of how scientific knowledge is created, it attempts to make students hold scientific knowledge as tentative so that they will be open to new ideas, and less likely to hold current scientific knowledge claims as absolute.

Discovery and Inquiry

What differentiates "inquiry", as discussed in the previous section, from "discovery"? Inquiry is meant to focus on the critical analysis of the processes involved in interpreting data, and on the process of justifying scientific knowledge claims, so that students can see how the knowledge gained is constructed and therefore tentative. Discovery methods tend to focus on the students' personal acquisition of the products of scientific activity, the scientific knowledge claim itself.

The discovery approach to laboratory work, which is largely credited to H. E. Armstrong (Brock, 1973) in the late 1800's, is seen in many forms in science curricula, but in general refers to any laboratory experiment or activity, whether structured or not, in which the results to be gained are unknown to the student at the onset of the work, as opposed to a laboratory activity that illustrates a principle that already has been learned. The goal of this approach is for students to "discover" the scientific knowledge for themselves, instead of having it told to them. More recently, Jerome Bruner advocated this method of learning, not only for science, but for many subject areas. Discovery, he asserts,

> whether by a schoolboy going it on his own or by a scientist cultivating the growing edge of his field, is in its essence a matter of rearranging or transforming evidence in such a way that one is enabled to go beyond the evidence so reassembled to new insights. (Bruner, 1962, p. 82)

The relationship between discovery and inquiry is delineated by Suchman (1962), as he describes the components of inquiry:

> [Inquiry] can be divided into four main types of actions: searching, data processing, discovery and verification. While none of these actions is unique to inquiry, they are all essential to it, and in combination, form a cycle of operations that characterize the inquiry process. (p. 5)

Thus discovery is a part of the inquiry process, and, as such it is very difficult to talk about one without the other, which may be one of the reasons why the terms get confused so often. An approach that focuses on teaching students how to proceed in finding out the answers to questions they might have, or on the processes involved in investigating, would be emphasizing inquiry; whereas an approach that stressed students acquiring scientific knowledge by themselves, whether the procedure for determining this knowledge is given to them or not, would be emphasizing discovery. To further confuse this issue is an approach that emphasizes students' discovery of the means of inquiry: students are taught how to inquire, not by specific instruction about various strategies or procedures, but by being presented with a problem or discrepant event and having to discover, or figure out for themselves, effective strategies for investigating it. This approach, which involves students behaving in an autonomous, self-directed fashion, rather than following a set of instructions, is what many writers (Bruner, 1962; Ivany, 1975; Suchman, 1962) mean when they use the word "inquiry".

Whether learning by discovery and inquiry laboratory approaches is autonomous or not depends, to a large extent, on the age of the student. In elementary grades a completely autonomous learning approach is more likely to be used, whereas as the students progress into junior and high school, the learning is much more likely to be guided. For example, a science curriculum that has used autonomous inquiry and discovery learning as one of the main themes is Nuffield Foundation's Science 5/13 (1972). The curriculum materials consist of a series of books for the teacher that provide suggested topics and questions that the student may want to investigate. Students, between the ages of 5 and 13, that are taking this course are free to inquire into any subject they wish, and to develop questions that they want to answer. They are also responsible for deciding how they are going to find answers, and for determining the limitations on the answers that they derive. In a class, several groups may be working on different problems, with the teacher acting as a guide. If the methods that the students use are not efficient or effective, or if the answers determined do not seem to make sense, or do not have enough accuracy, students are encouraged to develop other methods or to try to repeat their experiments for greater accuracy. Communication between groups is encouraged, and students periodically report their findings and methods to the rest of the class.

As students go from elementary to junior high and beyond, the importance of scientific knowledge acquisition leads to a discovery approach that is much more teacher-directed. Ivany (1975) describes this guided-discovery model of teaching as "a deliberate attempt to structure experiences for children so that through explorations they will be led to find out for themselves some of the basic ideas of science" (p. 136). The Nuffield Foundation Chemistry (1967) curriculum that follows Science 5/13 uses this approach. Students are encouraged to become actively involved in the investigation process so that "a picture of a limited area of the subject can be built up at first hand by the pupils' own efforts" (Nuffield Foundation, 1967, p. 2). While students are encouraged to discuss methods of investigating the various problems in the course, once the method is agreed, the students are directed to their lab books which describe the previously formulated method for doing the investigation -- an indication of how small the role that the student plays in making these decisions and how much leading the teacher does. It soon becomes obvious that the discovery learning of Science 5/13 and Chemistry are not the same thing. With more emphasis on the discovery of accepted scientific knowledge and less on inquiry skills, the teacher must make sure that students discover the correct concepts. Hodson (1990) is critical of the discovery approach for this reason:

> The real source of the problem is that teachers pretend to children that the purpose of such lessons is to engage in scientific enquiry (to 'discover'), when the real purpose is to promote the acquisition of particular scientific knowledge (the 'established facts'). (p. 37)

Any results that are unanticipated or misinterpreted, Hodson continues, may lead children to discover an alternative science. The usual response is to inform children that they have got the 'wrong result'. This instils a concern with what 'ought to happen' and a preoccupation with the 'right answer'. It also projects the view that scientists know well in advance the results of the experiments they conduct. (p. 37)

Thus discovery learning in secondary science is much more guided than in elementary schools; experiments are devised to illustrate specific scientific concepts, and, while students are involved in much hands-on activities and no doubt learn a great many laboratory skills and techniques, the similarity between scientific activity and science education is very small. Instead of encouraging intellectual independence, students may become overly dependent on the teacher and textbook to divulge right answers, and may exhibit a lack of confidence in their own abilities to inquire.

Science Fairs

Science fairs provide some of the infrequent opportunities for secondary science students to engage in an autonomous inquiry/discovery activity. Students have to develop a problem, devise and execute their own experimental method for solving it or studying it, and write a report or display their results to either their teacher, class, and/or judges. Two of the main objectives in science fairs are for students to imitate scientists as they do their projects, and "if they are effectively to complement the total science education program of a school, [science projects exhibited in fairs] should reflect the nature of science..." (Stedman, 1975). These objectives are reflected in the criteria that are suggested that judges use when evaluating the students work (Carlisle & Deeter, 1989; Hamrick & Harty, 1983; McBurney, 1978; Stedman, 1975), which usually include an evaluation of the students' illustration of hypotheses, procedures, interpretations, and conclusions.

Thus, while students are given the opportunity to inquire and discover scientific knowledge for themselves, and gain an appreciation for the work of scientists and the nature of science, they must do so within the constraints of the criteria of the judges and an outdated version of the scientific method in order to score well. According to some writers (Blume, 1985; Smith, 1980; Stedman, 1975), science fair projects should be experimental in nature if they are to portray the real nature of science and to give students practice at critical thinking. Model building, displays of information, or demonstrations of principles do not fare as well as exhibits that use the 'scientific method', even though for many scientists, like marine biologists and astronomers, model building and collecting information is one of their main activities. Thus discovery in a science fair usually means that the discovery has to be experimental.

A second criticism of science fairs is that they are too competitive (Burtch, 1983; McBride & Silverman, 1988). However, this competition could be likened to the influence that awards, grants and fellowships have on scientists. Opportunities for expanding the students' understanding of the motivation for scientific work would be expanded by discussions around this theme.

A third criticism of science fairs is that the projects are often the work of parents or teachers, and not the result of scientific thought on the part of the student. Thus, while science fairs ideally have potential for getting students at all ages exploring and investigating problems on their own, the takeover of projects by parents and teachers may often result in critical thinking skills not being encouraged.

A Process Approach

Teaching inquiry in a more teacher- or textbook-directed manner, sometimes called a 'process approach' to science, is another approach to laboratory work that gained prominence in the early 1960's and is still used today. Using this method, the activities of scientists are analyzed and categorized into separate 'processes' such as observing and quantifying. These scientific processes are then taught to the students, usually one at a time or with one process as the main focus, in a laboratory setting. Subsequently, laboratory activities that integrate all or most of the processes are done by students. At this point the whole scientific method is thought to be constructed and acquired. Advocates of this approach can be quite explicit about their intent in teaching science using this method. Gagné (1965), in describing the use of Science - A Process Approach (American Association for Advancement in Science (AAAS), 1970), likens teachers and students using this curriculum to participants in an experiment - "an experiment which itself attempts to follow and to use the methods of science" (p.1). The hypotheses of this experiment

> represent a serious and systematic view of how scientific capabilities may be developed within the human individual, of how he can become an adult who is attuned to the complexities of knowledge which represent our 'scientific' way of understanding the modern world. (p.1)

Three objectives for science education are to be met in Science - A Process Approach: vocational, citizenship and self-fulfilment. Thus, this course attempts to help students become scientists, and to foster an understanding of the ways of science and an appreciation of science. The processes of science that are identified are: observing, classifying, measuring, communicating, quantifying, organizing through space and time, making inferences and predictions, making operational definitions, formulating testable hypotheses, carrying out experiments, and interpreting data from experiments. As one of its key premises, at the end of instruction in the processes of science, Gagné asserts that students should be able to understand the works of scientists, after a listening to brief descriptions of their experiments.

Gagné also asserts that after learning science using Science - A Process Approach, any additional instruction in science should take only half as long, although he provides no reason for why this should be, or evidence that it is so.

Teaching the nature of science using a process approach is supposed to encourage intellectual independence in two ways. First, since all scientists are supposed to use the same processes in similar ways, students should be able to understand the reasons and evidence for scientific knowledge claims by discussing the matter briefly with a scientist, as Gagné claims. Second, by knowing and using the processes of science, students should be able to solve problems for themselves, that is, they should have a strategy for analyzing and generating their own knowledge. Armed with the processes of science, students should be able independently to assess any situation.

However, the encouragement of intellectual independence using a process approach alone is problematic. The main problem is that acquired skills are not much use if knowledge is lacking. For instance, knowing the processes of science does not necessarily enable one to comprehend the evidence that is generated by them. Having skill in observation techniques does not enable a student to analyze the spectra from an infrared spectrometer. Thus, it is unlikely that a student could understand the reasons and evidence that support many scientific knowledge claims simply by discussing briefly the matter with a scientist. It would be equally unlikely for students to use these process skills to solve problems in spectrometry.

Constructivist-Motivated Laboratories

A recent approach to laboratory work has been developed using a theory of knowledge called "constructivism". Broadly defined, constructivism is the process "whereby individuals through their own mental activity, experience with the environment and social interactions progressively build up and restructure their schemes of the world around them" (Driver, 1989, p. 85). Science, as a result of ideas undergoing publication and being "validated" by the scientific community, is socially as well as personally constructed. Thus, scientists have a shared view of the world involving concepts, models and procedures. Learning science, Driver asserts, involves being initiated into the culture of science. Herein lies the distinction between discovery learning and a constructivist approach:

> If knowledge construction is seen solely as a personal process, then this is similar to what has traditionally been identified as discovery learning. If, however, learners are to be given access to the knowledge systems of science,

> the process of knowledge construction must go beyond personal empirical enquiry. Learners need to be given access not only to physical experiences but also to the concepts and models of conventional science. The challenge lies in helping learners to construct these models for themselves, to appreciate their domains of applicability and, within such domains, to be able to use them. (Driver, 1989, p. 85)

A constructivist laboratory approach would take into account the child's experiences and preconceptions about science and attempt to encourage or change these conceptions to conventional scientific ideas through presentations of discrepant events (Carey, Evans, Honda, Jay & Unger, 1988; Driver, 1989; Driver & Bell, 1986). These events show inadequacies in the students' conceptions and force them to change their theories to more acceptable ones. Thus, while recognizing that knowledge is constructed individually, students are led to hold views that correspond to currently accepted views.

Justifications for using a constructivist approach to laboratory work primarily concern increased understanding of scientific content and fostering conceptual change. Carey, et al. (1988) justify using a constructivist approach also as a means of understanding the nature of scientific knowledge and reasoning: "We believe that students must learn to reason critically about scientific knowledge. It is crucial that students understand that the body of scientific knowledge... is constructed and changing, rather than 'the truth'" (Carey, et al., 1988, p. 1). The conceptual change that Carey, et al., propose in using a constructivist approach is not only content oriented, it also concerns scientific epistemology:

> Students' initial epistemological stance concerning scientific knowledge is that knowledge is a passively acquired, faithful copy of the world, and all one must do is find it by looking in the right places. In order for students to move beyond this conception, we believe that they must have opportunities to become actively engaged in construction and evaluating explanations for natural phenomena. (Carey, et al., 1988, p. 2)

Constructivism, then, focuses on students' evaluating their own beliefs about scientific concepts and theories, testing them, and attempting to come up with more accurate conceptions. Students can accept new scientific knowledge only when they are convinced that their own conceptions are inadequate, and see the body of evidence that supports the more acceptable conception.

Summary of Laboratory Approaches

The laboratory approaches described above have many commonalities and differences. All the approaches advocate putting experiment before theory, that is, having the students discover scientific knowledge claims by themselves. As such, all of these approaches emphasize scientific knowledge generation and acquisition by experimenting, or by confirming or discovering the scientific knowledge claim first hand. With these approaches, trust would not be even considered as a part of science, since the focus in experiments is to determine the evidence and reasons for oneself.

Second, with approaches that emphasize knowledge generation, teaching a scientific method or a means for generating reliable scientific knowledge is stressed. The resulting scientific knowledge is usually thought of as being proven; without an inquiry or constructivist emphasis that stresses the constructed or interpretive nature of scientific knowledge, the tentative nature of scientific knowledge is not emphasized. In this way, teaching the nature of science using the laboratory may have similar outcomes to teaching the nature of science using a history of science that includes only names, dates, and experimental details. That is, both approaches stress the evidence that supports scientific knowledge claims and the rationality of science. Students may not feel it appropriate to question such knowledge claims with such undisputable evidence supporting them.

Third, laboratory approaches that emphasize the processes and logic of scientific knowledge generation and problem-solving are justified as providing a means to intellectual independence and critical thinking. By providing models of scientific activity, or by having students inquire into discrepant events, the means to solve or analyze future problems or scientific knowledge claims is learned. This is typified by Gagné's statement about the ability of students to understand the work of any scientists after hearing a brief description, once they understand the processes of science. The scientific method, once mastered, is seen as the key to understanding the work of scientists and to independent problem-solving.

Fourth, if more than just the evidence and results were to be discussed, laboratory approaches could have a great deal of potential for illustrating the role of trust in science. Scientific ethics, accurate reporting of results, using the teacher and other students as examples of the peer review system, doing experimental work that relies on teams of students working together on different segments of the project (even in different scientific disciplines) and the explicit use of scientific knowledge that is unconfirmed by the students to generate more scientific knowledge, would illustrate the prevalence of trust in science. Even one of the greatest disadvantages of discovery approaches, that of students' obsession with discovering the "right" answer, could be used to illustrate the dogmatism and authoritarianism that is prevalent in science as opposed to the reliance on evidence and reason. Norris (1984) describes how many prominent philosophers (Kuhn, Popper, Lakatos) see a need for dogmatism in science, and concludes:

> If they [the students] are to be given an accurate view of the nature of science, then it might be necessary to show them instead the vital role that dogmatic positions play in furthering science. In this approach, dogmatism would be cast not so much as an evil to avoid but as a necessary stance which human beings must adopt in their attempt to gain new knowledge. (p. 490)

However, most labwork done in school is done on a individual basis with the emphasis on individual autonomy, not on communal consensus.

The Philosophy of Science

A third approach to teaching the nature of science is to teach, either explicitly or implicitly, philosophy of science. While much has been written on the necessity of students' being educated in the philosophy of science, there is little consensus among the authors about what is to be taught. It is common to read one article strongly advocating a realist perspective of scientific theories while denouncing the instrumental position, then to read a second article that advocates just the opposite. It is also common for authors to hold positions that are intermediate to opposing views, and for hybrid positions to arise.

The most common foci in teaching the philosophy of science include instruction in the methods of scientists and how science progresses, the nature of scientific theories, and the nature of scientific knowledge. In this section a brief outline of some of the more prevalent positions in each of these areas will be analyzed to see whether holding these positions offers any means of attaining intellectual independence or fostering critical thinking.

The Progression (or Nonprogression) of Science

In this section common views on how science progresses will be analyzed. These will include inductivist and falsificationist positions, as well as the positions of Kuhn and

Feyerabend. These analyses will be brief and undoubtedly incomplete, and, as stated above, are not meant to describe all the different positions on how science progresses.

Inductivism. In this view of the progression of science and the generation of scientific knowledge, scientists record their unprejudiced objective observations, and from a large number of these theory-free observations develop generalizations, or universal laws. Science progresses

> as the number of facts established by observation and experiment grows, and as the facts become more refined and esoteric due to improvements in our observational and experimental skills, so more and more laws and theories of every more generality and scope are constructed by careful inductive reasoning. The growth of science is continuous, ever onward and upward, as the fund of observational data is increased. (Chalmers, 1982, p.5)

Inductive generalizations, because they can be falsified by just one contrary observation, must be held as tentative, and cannot be proven true.

Most philosophers of science do not think that the inductivist view of scientific progress is accurate. It holds that scientific observation is completely theory- and prejudice- free, and is the starting point of experimental work. Philosophers such as Hanson (1958) and Kuhn (1962) have shown convincingly how theory influences observation, and have maintained that, contrary to the inductivist position, theory precedes observation.

The inductivist view of the progress of science has long been discarded by most philosophers of science. Yet many science curricula have laboratory experiments that are based on generating scientific knowledge using inductive generalization, and the theory-free nature of observation statements is widely proclaimed in students' laboratories advising them to separate observation statements from inferences, and to observe objectively. While few, if any, current authors in the field of science education advocate this view of the progression of science, its presence is still evident in laboratory manuals and science textbooks.

Falsificationism. Karl Popper advocated this view of the progression of science with his book The logic of scientific discovery (1959). He maintained that science advances by scientific theories being proposed by scientists who then attempted to falsify them. Scientific knowledge was generated by making predictions based on the proposed theories; if evidence arose that was contrary to the theories, they would be discarded. Chalmers (1982) depicts the progression of science according to the falsification position as such:

> Only the fittest theories survive. While it can never be legitimately said of a theory that it is true, it can hopefully be said that it is the best available, that it is better than anything that has come before. (p. 38)

The falsificationist view of the progress of science still has a lot of support from many philosophers of science. Its premise that scientific knowledge must always be written in a form that is testable by evidence or observation is often used to demarcate scientific knowledge from other forms of knowledge. By holding all scientific knowledge claims as potentially falsifiable, this view also emphasizes the tentative nature of scientific knowledge, which is an area of concern for many science educators. In order for students to think critically about science, and not view scientific knowledge as absolute and beyond reproach, they must hold a tentative view of scientific knowledge.

Kuhn's Position. Thomas Kuhn advanced a theory of the progression of science based on the views that scientists throughout history had not tried to falsify the theories that had been proposed, and that theories were not always discarded in the face of conflicting evidence. On the contrary, scientists tended to hold onto theories, ignore anomalies, and promote theory change only when enough anomalies accumulated to force a scientific crisis and when a theory had been proposed that would account for the anomalies. Thus, science had two phases. Normal science occurs when work is done to expand scientific knowledge according to the existing scientific paradigm. (A paradigm can be thought of as the general theoretical assumptions, laws and methods that the scientific community adopt.) Kuhn referred to this activity as "puzzle solving". During the period of normal science, scientists are uncritical of the paradigm so that as much knowledge can be gained from it as possible. As anomalies begin to accumulate, a period of revolutionary, or extraordinary, science follows. In this stage, the underlying assumptions of the existing paradigm are questioned and a new theory proposed with different assumptions. In many cases, the old and new theories are incompatible, or as Kuhn described, incommensurable. Since the rival theories have different underlying assumptions, theory change is a very complex process, since what is legitimate or meaningful to one paradigm may oe meaningless to its rival. Chalmers (1982) states: "the kinds of factors that do prove effective in causing scientists to change paradigms is a matter to be discovered by psychological and sociological investigation" (p. 97). This theory of the progression of science has become increasingly popular and has caused many philosophical debates. However, it has not gained prominence in science curricula, perhaps due to the depiction of theory-change being an partly irrational and relativistic process.

Feyerabend's Position. An anarchistic change theory was advanced by Paul Feyerabend. He denounced all previous methodologies of science and made his renowned statement, "All methodologies have their limitations and the only "rule" that survives is 'anything goes'" (Feyerabend, 1975, p. 296). He studied the history of science and held that there was no one set of rules that guided scientists in matters of theory choice. He also held that rival theories may be incommensurable since

> in some cases the fundamental principles of two rival theories may be so radically different that it is not possible even to formulate the basic concepts of one theory in terms of the other with the consequence that the two rivals do not share any observation statements. In such cases it is not possible to compare the rival theories logically. (Chalmers, 1982, p. 137)

Feyerabend also holds that science is not superior to other forms of knowing, such as magic or astrology. Since they have different underlying assumptions, they are incommensurable, and therefore incomparable. He is a strong advocate of individual freedom, be it freedom to choose the method one wants or freedom to choose between science and other forms of knowledge.

Summary. While each view of the progression of science has vastly different emphases, justifications for teaching them do have something in common. All the views try to impart a picture of how scientific knowledge is subject to revision. None of the views intend to portray the view that scientific knowledge is true or static, but is changing and growing as our means of experimenting have expanded.

Inductivist and falsificationist views of science tend to emphasize the rational side of science; the experimental evidence for scientific theories and the means for generating reliable scientific knowledge are stressed, while personal or social factors are ignored. Scientific thinking using a scientific approach or method, may be one of the intended outcomes of these approaches.

More recent views on the progression of science, as exemplified by Kuhn and Feyerabend, emphasize the relative and perhaps nonrational nature of theory change, and thus emphasize even more the tentative nature of scientific knowledge. These views hold that many theories are incommensurable, and, as such, analyzing the evidence and reasons supporting them is inadequate as a method for assessing the soundness and acceptability of a scientific knowledge claim. This can be done only by a community of scientists, and decisions are influenced by societal, economic and personal factors. All of these factors would need to be considered by students in analyzing past scientific theory change. Analyzing the soundness of scientific theories being put forward today or in the future, however, is too complex a process to be done by one individual. To assume that it could be undertaken by one person is to misrepresent the way scientific theories are accepted and assessed, according to Kuhn and Feyerabend.

The Nature of Scientific Theories

A second aspect that is commonly the focus of instruction in the philosophy of science is that of the nature of scientific theories. There seem to be two extreme and opposing positions in this debate, each one with strong advocates. These are realism and instrumentalism. These views will be discussed here briefly, as well as a hybrid position put forward by Hodson (1982), again with the intention of analyzing the ability of instruction in this matter to increase students' critical thinking abilities and intellectual independence.

Realism. This view of the nature of scientific theories holds that scientific theories describe what the world is really like. The entities described in scientific theories, like electrons, molecules, and magnetic fields, have actual ontological status. The aim of science is to get better, more accurate and true descriptions of the world.

Instrumentalism. According to an instrumentalist, scientific theories do not describe the world as it actually is; theories are "nothing more than sets of rules for connecting one set of observable phenomena with another" (Chalmers, 1982, p. 148). Instrumentalists hold that there is a difference between observable entities and theoretical concepts; while observable entities are given ontological status, theoretical concepts are not. The products of science (theories) are not viewed as right or wrong, instead they are judged by their usefulness in connecting to observations.

Hodson's Position. Hodson describes a view of the nature of scientific theories that is intermediate to realism and instrumentalism. In this view, some theories have instrumental status, or are nothing more than useful models, but as more and more evidence corroborates these models they take on a realistic status. He states that "A realist can be realist about some theories (those which he believes to be true) and instrumentalist about others, which he finds useful but not true (i.e. theoretical models)..."(1982, p. 25). The job of educators and textbooks, in his view, is to let students know the status of theories so they will able to judge appropriately the nature of the various theories as models or depictions of reality.

Summary. The instrumentalist and realist views of the nature of scientific theories seem directly to oppose one another, and a consensus about which view is the best is not imminent. Many writers (Selley, 1989, and Chalmers, 1982, for example) advocate intermediate positions. Teaching one or even several views would serve to encourage students to evaluate just what the theories are supposed to represent. However, they would not be in a position to evaluate which position most accurately portrays scientific theories. Both views hold that scientific knowledge is subject to revision: realists would revise their theories as technological advances allow different perspectives about reality, and instrumentalists as new models or theories connect to a wider variety of observations.

The Nature of Scientific Knowledge

There are several terms used in describing the nature of scientific knowledge. Many of the terms are related; they are not meant to be mutually exclusive. Some commonly used terms in discussing scientific knowledge are "objective", "constructed", "individual", "subjective", "consensual", "rational", "relative", "absolute" and "tentative". These terms will be discussed briefly in this section in order to see whether different perspectives on the nature of scientific knowledge encourage critical thinking and intellectual independence.

One way scientific knowledge can be conceived of is as objective. This is a view that "stresses that items of knowledge, from simple propositions to complex theories, have properties and characteristics that transcend the beliefs and states of awareness of the individuals that devise and contemplate them" (Chalmers, 1982, p. 113). That is, theoretical constructions are thought to represent entities that exist independently of the knower, and have properties that may go beyond what was originally intended when they were postulated. This view has support in explaining how consequences not thought of originally can result from scientific theories. Chalmers uses the example of

Poisson's discovery of a bright spot, a consequence of Fresnel's wave theory of which Fresnel was unaware, to

> provide persuasive evidence for the view that scientific theories have an objective structure outside of the minds of individual scientists and have properties that may or may not be discovered or produced and may or may not be properly understood by individual scientists or groups of scientist. (p. 117)

Three related terms are constructed, individual or subjective. Scientific knowledge, if described using these terms, is dependent on the knower and is better understood as a set of beliefs that the scientist has. Confrey's (1990) view of knowledge typifies these terms. She states that

> all knowledge is necessarily a product of our own cognitive acts. We can have no direct or unmeditated knowledge of any external or objective reality. We construct our understanding through our experiences, and the character of our experience is influenced profoundly by our cognitive lens. (p. 108)

The way scientific knowledge is socially constructed provides some support for a constructivist or subjectivist view of scientific knowledge. Glasersfeld (1991) argues this point when he asserts,

> the fact that we do agree on certain things and that we can communicate does not prove that what we experience has objective reality in itself. If two people or even a whole society of people look through distorting lenses and agree on what they see, this does not make what they see any more real - it merely means that on the basis of such agreements they can build up a consensus on

certain areas of their subjective experiential worlds. (p.xv)

Thus the various scientific knowledge claims, according to these views, will have different meanings for different scientists, depending on their beliefs and experiences.

Another term used to describe a view of scientific knowledge is consensual. Knowledge is generated, justified and held by communities of scientists. It is not up to individual scientists, according to this view, to judge the soundness of a knowledge claim:

> Recent work in the sociology of science has shown with a wealth of detail that the standards of the assessment of the worth of scientific products are located in and peculiar to quite specific communities... Science is a communal practice with communal standards of good work." (Harré, 1986, p. 13)

In order for a scientific knowledge claim to be accepted it must meet the standards of a scientific community. Scientists are "fundamentally and vitally dependent upon the good will of those practitioners within the area who set the standards not only of acceptability but also of plausibility" (Code, 1987, p. 232). Thus a consensus among the scientific community about the worth of a scientific knowledge claim is necessary for its acceptance as valid scientific knowledge. The evidence necessary to judge the claim must meet the communal standards set by the community of scientists.

A term that is sometimes used in conjunction with the term "objective" is rational. This view of scientific knowledge holds that there are universal criteria that can be used to judge whether a theory is good or bad. A good theory, according to this view, does not depend upon social, historical or economic conditions; it can assessed without reference to these factors. Siegel (1989) strongly argues for the view of science as a rational process: "What insures that rationality is the commitment to evidence - or, better, science is rational to the extent that it proceeds in accordance with such a commitment" (p. 14). This view treats scientific evidence as ahistorical, able to be assessed on its own worth at any time.

Contrary to this is the view that scientific knowledge is relative. This view holds that theories cannot be assessed as good or bad, for "what counts as better or worse with respect to scientific theories will vary from individual to individual or from community to community. The aim of knowledge-seeking will depend on what is important for or what is valued by the individual or community in question. " (Chalmers, 1982, p.102). Any analysis of any scientific knowledge is not complete, according to this view, until all social, historical and economic factors have been assessed. Thus a good theory is judged on the basis of how useful it is to a particular community, not on some universal criteria.

Controversy about which of the above terms best portrays scientific knowledge is common among many philosophers of science and science educators. The final pair of opposing terms used to describe scientific knowledge, tentative and absolute, are probably the only terms upon which a consensus has been reached (Ennis, 1979). A view that scientific knowledge is tentative would hold that scientific knowledge is constantly changing and undergoing revision, whereas a view that holds scientific knowledge as absolute would view it as static, unchanging and final. On this point, science educators and philosophers are agreed: scientific knowledge is tentative (Ennis, 1979).

In summary, instruction in the nature of scientific knowledge, as in the other areas of the philosophy of science, seems to have little consensus and much diversity. One could portray scientific knowledge as rational and objective, with a focus on the experimental evidence that justifies scientific knowledge. This portrayal may be more common when the desired outcomes of science education are promoting conceptual change to accepted scientific beliefs, achieving a good understanding of the rational basis for current scientific knowledge, and/or increasing the ability to assess the reasons for theory changes. Student could be said to be intellectually independent when they understand and can assess for themselves the evidence for scientific knowledge claims.

On the other hand, one could portray scientific knowledge as individual, constructed and relativistic. The emphasis in these accounts on the theory-laden nature of observation, and on the need to take factors other than experimental evidence into consideration when assessing scientific knowledge claims, encourage a more humanistic and nonrational view of science. This would probably be more common when the emphasis in science instruction is on tentativeness in science, questioning the products of science, or the portrayal of the humanistic, social and perhaps nonrational side of science. These views of scientific knowledge may enhance the students' critical dispositions towards scientific knowledge.

It is important to realize that some of the views of scientific knowledge hold that individuals cannot assess the soundness of a scientific knowledge claim. Holding a consensual view of scientific knowledge would view the scientific community as the assessors of scientific knowledge. Relativistic views of scientific knowledge hold that any assessment of scientific knowledge will depend upon social and economic factors; the evidence used in assessing knowledge claims is only one factor to be taken into account in the assessment. If intellectual independence, or the ability to assess the soundness of scientific knowledge claims on one's own, is a goal of science education, then these views of scientific knowledge would probably not be conveyed to students. Thus, while these views would hold that intellectual independence is not possible for science students, or scientists for that matter, they would encourage a more sceptical or tentative view of science, since they portray the social and economic factors that must be assessed along with the scientific evidence.

In this section, ways of viewing scientific knowledge have been described. No attempt to analyze how scientific knowledge is actually conveyed to students has been undertaken. Thus, while some philosophical views of the nature of scientific knowledge, such as the consensus view, do acknowledge the role of trust and testimony in science, it is uncertain whether these views are being imparted to students. I suspect that they are not; however without any curriculum analysis or empirical study of the philosophical content of science classes, this suspicion is unconfirmed. Philosophical discussions on the nature of scientific knowledge do seem to have potential for imparting a view of the role of trust and testimony in acquiring scientific knowledge.

Synopsis of the Three Approaches to Teaching the Nature of Science

This chapter presented three approaches to teaching the nature of science to students, namely, using the history of science, laboratory activities, and the philosophy of science. With the exception of the approach to teaching the history of science by giving only the names, dates and discoveries of scientists, all approaches focus on the analysis of the evidence and reasons that support scientific knowledge claims, and the methods that scientists use to generate and justify their knowledge claims. Each approach also holds different expectations about how students may be able to achieve intellectual independence and critical thinking skills. These expectations will be examined in the next chapter and juxtaposed with the assertions regarding the interdependence of scientists, epistemic dependence and necessity of trust in science.

Chapter Five

Conclusions

Teaching the nature of science as a means of achieving intellectual independence and increased critical thinking abilities has been shown to be a long-standing goal of science education. However, the ability to be intellectually independent and to be able to think critically about scientific knowledge is questioned by Hardwig, as well as others, who argue that there are many instances in which all people are necessarily epistemically dependent on scientists. Different approaches to teaching the nature of science were examined for their portrayal of scientific epistemologies and to see the means that they offer for achieving intellectual independence and critical thinking skills. In this chapter the expectations about students' abilities to achieve intellectual independence and critical thinking skills are juxtaposed with the epistemic dependence claims made by people like Hardwig, Broad and Wade, and Siegel, in an effort to see if there is any way in which students can have independence over, or think critically about, scientific knowledge claims. In the final chapter, the implications of epistemic dependence for teaching the nature of science are addressed.

Expectations of Intellectual Independence and Critical Thinking Abilities

The examination of the various approaches to teaching the nature of science in the previous chapter shows at least four ways in which students are expected to achieve intellectual independence and/or think critically about science. Each of these ways vary in the amount of independence that the students are expected to have over scientific knowledge claims, from complete to lesser degrees of independence. The ways can be described as follows:

1. Complete independence: Students are expected to be sceptical of all knowledge claims and attempt to verify or confirm all knowledge before they accept it. This position would involve the students in replicating the work of other scientists or discovering new knowledge on their own. Testimony is not an acceptable means of acquiring new knowledge in this form of science education.

This expectation of the degree of independence that students would be able to exhibit is typical of the epistemologies espoused by a laboratory approach to teaching the nature of science. Discovery and inquiry techniques that emphasize knowledge generation and problem solving using only the laboratory and first hand experimentation may encourage this expectation of students. Another approach that may encourage this expectation for students would be the historical approach in which past experiments are replicated in order to confirm findings. Instruction in the philosophy of science that tends to focus on scientific epistemologies that are based only on experimentation may also encourage this expectation for students.

2. Independence with respect to evidence and reasons: Students are expected to understand or be able to evaluate the reasons or evidence for believing scientific knowledge claims. This position would not necessarily involve the students' learning by experiencing first-hand all the experiments that support scientific knowledge, but would expect that students understand how the experiments are done and how the observations are interpreted, and thus be able to decide whether the justifications for the knowledge claims are sound. Since students would not be doing the actual experimental work, some testimony would be relied upon, and students would have to trust that the scientists actually got the results that they did. However, this reliance on trust and testimony may not be acknowledged by the teachers or textbook.

This second expectation of students is typical in approaches that include historical accounts of science with details included about experimental work. Instruction in the philosophy of science that portrays science as a rational, objective endeavour would also emphasize the evidence and reasons for scientific knowledge claims, and may encourage in students the attitude that one must understand the evidence and reasons for knowledge claims before one can admit to knowing them.

3. Independence with respect to the source: Students may not understand how scientists performed the experiments upon which they depend for their scientific knowledge, but they are expected to be able to be critical about the source of the knowledge. In this position, epistemic dependence upon the expert is acknowledged, but the attempt rationally to ground beliefs is made by deciding whether the expert is indeed an expert, whether he or she can be trusted, whether there is any conflict of interest that may cause the expert to distort what he or she believes, and so on. This expectation is best described by Siegel (1988).

This expectation may not be that common for science students. Scientists are usually portrayed as beyond reproach and completely trustworthy. Historical accounts of complex theories may encourage this type of analysis for students. For example, instead of assessing Einstein's theory of relativity, or Schrödinger's wave equation, teachers may appeal to the expertise of Einstein or Schrödinger. Also, historical accounts of past scientists that have defrauded the scientific community by publishing distorted or fabricated results would also encourage students to scrutinize the integrity of scientists making knowledge claims. Instruction in the philosophy of science that focuses on the influences that affect the work of scientists, such as discussions on the pressure to publish, and the economic and social pressures on scientists, may encourage this level of assessment.

4. Independence with respect to judging the certainty of the scientific claim: This

expectation is based on the premise that students, if they understand how scientific knowledge is generated, will hold scientific knowledge as tentative. Their independence is exhibited in their willingness to suspend judgement instead of dogmatically accepting all scientific knowledge claims as the truth. This expectation takes into account that students may not be able to understand how an experiment was done or how the results were interpreted. They also may not be capable of critically analyzing the source of the knowledge claim for a variety of reasons: the scientist that performed the experiment could be long dead or so obscure that reliable biographical knowledge on the scientist is lacking, or the ability accurately to judge the character of a scientist may be undermined by the fact that so many reputable and well-respected scientists have committed some form of scientific fraud. The students' only subject for evaluation is the generic knowledge of the processes of science and the way scientific knowledge is constructed. Scepticism is held about scientific knowledge claims that they are unable to evaluate without any foundation for disbelief or belief, since they are unable to assess either the source or the reasons and evidence supporting the knowledge claim. This position is described by Hardwig (1991) and Broad and Wade (1982).

Many of the approaches to teaching the nature of science hold this expectation for students. One of the underlying themes of all historical accounts of science concerns the revisionary nature of scientific knowledge. Laboratory approaches, such as Schwab's enquiry approach, that emphasize the way that scientific knowledge is constructed from the mind of scientists instead of "discovered" also emphasize the tentative nature of science. One of the major emphases in instruction in the philosophy of science is on the tentative nature of scientific knowledge and theories -- one of the few noncontroversial subjects in the philosophy of science.

The Attainment of Intellectual Independence and Critical Thinking Abilities

Four levels of independence or criticalness have been described in evaluating the expectations for science students after instruction in the nature of science. In this section, these four expectations will be evaluated in light of epistemic dependence claims to see if they are reasonable.

Complete Independence

Hardwig (1991) dismisses the ability of students to replicate most of the work of contemporary, and even past, scientists. He points out, as described in chapter three, that due to restrictions in time, expertise and expense, replication is not a feasible alternative for most scientists, let alone laypeople. The philosophical basis for this expectation is not sound, either. Most philosophers now acknowledge that scientific knowledge is not verified by one individual, but is verified through a complex interaction among members of the scientific community, and that social and economic factors play a role. Thus asking students to assess the soundness of scientific knowledge on their own is very unreasonable.

Independence with Respect to Evidence and Reasons

For many of the same reasons cited above and in chapter three, this expectation appears unrealistic. Many team research projects have no one person that knows all the reasons and evidence for the scientific knowledge claims generated. Laypeople do not have the necessary expertise to interpret the data that are generated by advanced scientific instruments. Thus for many scientific knowledge claims being made today, and even many that have been made in the past, the expectation of achieving independence by understanding the reasons and evidence that support these claims is unrealistic.

Independence with Respect to the Source

This expectation of the level of independence that can still be attained even if evidence and reasons can not be understood by a layperson is discussed by Siegel (1988) and Norris (1990). However, Hardwig (1991) and Broad and Wade (1982) cast doubt on the reliability of this analysis. Respectable and often-published scientists have been found to be fraudulent, or have fraudulent people working under them with little or no supervision. Notwithstanding this, the difficulty in obtaining enough information in order to make a judgement on the credentials of an individual scientist (assuming that the scientist is working alone) make this approach to achieving independence dubious at best. Even if a sufficient amount of information about the scientist is available, the layperson often is unable to interpret it.

Independence in Judging the Certainty of Scientific Knowledge Claims

Instruction in the nature of science is often justified as a means to decrease scientism, -- "a belief that the scope of scientific authority is unlimited and beyond reproach" (Duschl, 1988, p. 52). Holding a tentative view of scientific knowledge is necessary for this. Since the evidence and reasons that support scientific knowledge claims, and the character and competency of the source, do not need to be analyzed in order to hold a tentative view of science, this very limited degree of independence is attainable. Students remain largely epistemically dependent on the scientific experts, however, and have limited means for questioning scientific knowledge claims. They are aware only that the knowledge claims could be revised later.

However, simply holding a tentative view of science is not sufficient for thinking critically about science. In order to think critically about science, one must have both the ability and the disposition. In many instances, the analysis of the evidence, reasons, and source of scientific knowledge is beyond the level of expertise of the student. Since this analysis is necessary for thinking critically about science, students cannot think critically about knowledge claims in such situations. In holding a tentative view of scientific knowledge, students may have a disposition to think critically about science, but not the ability.

Instruction in the nature of science may result in students being capable of achieving an independence in judging the certainty of scientific knowledge claims. By knowing that scientific knowledge is not proven or true, but is subject to change, they will not accept dogmatically every scientific pronouncement as the literal truth. Holding a tentative view of science may increase a student's disposition to think critically about science, to make a student more likely to question the evidence, reasons and the competence of the source. However, instruction in the nature of science is unlikely to enhance the ability to think critically about science.

Chapter Six

Implications

It was concluded in the last chapter that instruction in the nature of science may be effective in providing a means for students to achieve an independence in judging the certainty of knowledge claims, that is, students may not necessarily hold all scientific knowledge to be true or proven but instead may hold such knowledge to be tentative. Holding this view of the nature of scientific knowledge may increase students' disposition towards thinking critically about science, but will not necessarily increase their ability to do so. Without the ability to analyze and assess the soundness of scientific knowledge claims, students will be epistemically dependent on scientists for much of their scientific knowledge.

These conclusions have several implications for science education and instruction in the nature of science. In this chapter, implications regarding the epistemologies espoused in teaching the nature of science, justifications for teaching the nature of science, and instruction in scientific ethics will be discussed.

Scientific Epistemologies

Hardwig (1985 & 1991), Polanyi (1946) Broad and Wade (1982), and Code (1987) all have concluded that trust and reliance on testimony are necessarily a part of science knowledge acquisition. Any instruction in the nature of science should acknowledge the interdependence of scientists, scientists' own epistemic dependence in areas outside their expertise, and the lack of replication in science. However, approaches to teaching the nature of science still emphasize the role of experimentation, the analysis of reasons and evidence in scientific epistemology, and the principle of replication. Historical accounts offer details of experiments that lead to famous discoveries, laboratory approaches offer instruction in generating and justifying scientific knowledge claims, and instruction in the philosophy of science emphasizes the role of experimentation in the progress of science, as well as the status of the products of these experiments. Of course, these ways of knowing do play an important and pivotal role in scientific knowledge generation and justification. However, testimony also plays a major role when it comes both to knowledge generation and acquisition. The distinction between scientific knowledge generation, justification, and acquisition needs to be made in order to portray accurately the nature of science.

All three approaches to teaching the nature of science, that is, teaching the history of science, using a laboratory approach and teaching the philosophy of science, have potential as means to portray the role of trust and the reliance on testimony in science. Historical accounts that show how scientists frequently used the results of other scientists instead of verifying them for themselves would serve to illustrate the role of trust, as well as accounts of how some scientists have been found to betray the trust of the scientific community by publishing forged or distorted results. In this way the advantages and pitfalls of trusting the testimony of scientists are portrayed. For example, science can be shown to progress efficiently and effectively if scientists do not have to start from scratch every time they do research, and people would benefit from technological advances and scientific research that they may not understand. The disadvantages are also portrayed by illustrating the cases of research fraud. However, while these should serve as a warning about the way that trust can be betrayed, the large amount of reliable research that is done relative to the occurrence of scientific fraud should be conveyed to students so that they will not become overly sceptical or cynical about science. It should be shown that the advantages of relying on testimony outweigh the disadvantages, that to reject all scientific knowledge because it is has not been personally confirmed would mean regressing to the stone age.

Laboratory approaches also have potential for illustrating the role of trust and the reliance on testimony. Using the results from instruments that operate in manners beyond the expertise of the students does not stop the students from using them; the students must rely on manufacturers' and their teachers' testimony that they give the results that they are supposed to. (The teachers themselves may not understand exactly how the instruments work.) The process of writing reports may be likened to submitting an article to be published, in that the teacher must trust that the students actually obtained the results that they said they did. Working in teams with each member responsible for collecting different data would also serve to illustrate the interdependence of scientists. Teachers also should emphasise that the main role in experimentation is in scientific knowledge generation and justification, but is not the primary means used in scientific knowledge acquisition.

Instruction in the philosophy of science could also include discussions about the role of trust and the reliance on testimony. Instruction in scientific epistemologies could introduce the reliance on testimony as one of the foremost ways of knowing, especially for scientific knowledge acquisition. Instruction about the nature of scientific knowledge could include discussions surrounding its consensual nature so that students would understand that scientific knowledge is held and justified by communities of scientists rather than individuals. The practice of replication of experiments could be discussed in a more realistic vein; instead of emphasizing its virtues in detecting fraud, replication could be conveyed as a practice that, while valued by the scientific community, is rarely performed.

Thus teaching the nature of science, if it is to be conveyed accurately, should acknowledge the interdependence of scientists and the role of trust and testimony in scientific knowledge acquisition. The way scientists are perceived by students could affect decisions they make regarding their future in science. If scientists are portrayed as being omniscient, experts in all scientific endeavours, or, in the weaker sense, are portrayed as having the ability to analyze and evaluate any situation that they so choose by employing "the scientific method", students will not only get a false picture of what scientists are like, but will also be unlikely to think of themselves as capable of becoming one.

Justifications for Teaching the Nature of Science

Teaching the nature of science has often been justified as a means of increasing students' intellectual independence and critical thinking skills. However, this justification needs to be rethought. It was concluded in chapter five that instruction in the nature of science cannot increase students' intellectual independence with respect to the ability to assess the soundness of many knowledge claims or the competency of their sources. In a very limited way, it can increase students' independence with respect to judging the certainty of scientific knowledge claims and thus make them more disposed to think critically about science. However, without the ability to think critically about science, this disposition may be counterproductive.

Students that are sceptical of scientific knowledge without having any grounds for their belief may become cynical about science and its products (Norris, 1984). Holding a tentative view of the products of knowledge may lead students to distrust or disregard all scientific knowledge because "it is all incorrect and is likely to lead us astray" (Norris, 1984, p. 486).

Hardwig (1991) offers another alternative. Instead of trying to encourage a sceptical attitude towards science, trust in the scientific community and the products of science should be encouraged. In his view, we have no choice but to trust, since replication of experiments is rarely performed. He asserts:

An untrusting, suspicious attitude would impede the growth of knowledge, perhaps

> without even substantially reducing the risk of unreliable testimony. Trust in one's epistemic colleagues is not, then, a necessary evil. It is a positive value for any community of finite minds, provided only that this trust is not too often abused. For finite minds can know many things only through epistemic cooperation. (Hardwig, 1991, p. 707)

Thus trust, and not scepticism, may be more a productive attitude to have when it comes to acquiring scientific knowledge claims. This attitude will be more easily accepted and encouraged if the trust that is pervasive throughout the scientific community is portrayed when teaching the nature of science. Students will see that scientists and laypeople alike must rely on testimony for much of their knowledge.

Teaching the nature of science may still be justified, even though it may not increase students' ability to assess the soundness of many scientific knowledge claims that they may encounter upon leaving school. Instruction in the nature of science that integrates historical accounts, laboratory approaches, and philosophy of science may increase students' understanding of the scientific concepts and theories that they learn in school and may be effective in promoting conceptual change. It may also be justified as a means of making science classes more interesting to students, and as a means of attracting more students into science careers. There are many good reasons for continuing to teach the nature of science. However, fostering intellectual independence and giving students the ability to think critically about scientific knowledge claims that they encounter upon leaving school are not among them.

Instruction in Scientific Ethics

The rarity of replication in science and the reliance on testimony in scientific knowledge generation and acquisition leads to an oft-neglected but necessary area for instruction: scientific ethics. This would not be necessary if science was self-policing; the lack of emphasis on scientific ethics in science education may be due to the perception that science is self-policed. With instruction in the nature of science that demonstrates the reliance on testimony and the rarity of replication in science must come instruction in scientific ethics. Hardwig (1991) asserts:

> Inability to see the role of trust in science effectively destroys our ability to combat unreliable scientific testimony. It undermines any attempt to formulate and teach research ethics and it stifles any attempt to introduce new deterrents to fraud. A fraud-proof institution has no need for additional protection against fraud. (p.707)

By teaching that the scientific method is a commitment to evidence, as Siegel (1983) suggests, and that scientists are guided by reasons and evidence, instruction in scientific ethics is not warranted since scientists are seen as confirming all knowledge claims. However, as described in chapter three of this thesis, scientists do not often replicate other scientists' work. With the growing interdependence of scientists due to team projects, and with scientific knowledge becoming increasingly more complex and less likely to be replicated, instruction in scientific ethics is becoming an even greater necessity. Science courses should include objectives related to scientific ethics in their curriculum.

Summary

Teaching the nature of science has often been justified as a means of increasing students' intellectual independence and critical thinking skills with respect to scientific knowledge claims that they may encounter upon leaving school. However, scientists and students alike are inescapably epistemically dependent on other scientists for much of their knowledge. Scientific knowledge acquisition is achieved mostly through the reliance on the testimony of scientific experts. Analysis of three approaches to teaching the nature of science illustrate that intellectual independence is expected to be achieved to various degrees. Realistically, however, the most that could be expected for students is the last level of independence, that of independence with respect to judging the certainty of scientific knowledge claims. Critical thinking skills are enhanced to the extent that students may have a critical disposition towards scientific knowledge if they hold scientific knowledge to be tentative. However, instruction in the nature of science does not give students the ability to think critically about scientific knowledge claims. Implications for science education include providing instruction in the nature of science that acknowledges the role of trust, the reliance on testimony, and the interdependence of scientists in the acquisition of scientific knowledge. While students cannot achieve intellectual independence from instruction in the nature of science, their awareness of the reliance on testimony should encourage them to trust the testimony of scientists as an alternative. Finally, the necessity of trust and the reliance on the testimony of scientists makes instruction in scientific ethics a necessity in science education.

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