# History and Philosophy of Science in the Science Classroom

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# Chapter 1

## The Physics Curriculum, an Example of Science Teaching

*When compared to teacher effectiveness, student ability, time on task, and the many other things that influence learning, curriculum does not appear to be an important factor.*

(Arnold Arons, physicist and noted physics educator)

*The measure of scientific literacy is the measure of cultural awareness. The traditional science curriculum leaves students foreigners in their own culture. A problem in bringing about the essential reform of science teaching is that there are too many scientists that are scientifically illiterate and too few philosophers, sociologists, and historians of science and technology who are interested in pre-college science education.*

(Paul Dehart Hurd, 1987)

*Good teachers can rescue the worst curriculum, and bad teachers can kill the best.*

(Anon.).

**Introduction**

In an ideal world, the teaching of science would be guided by a curriculum, based on sound pedagogical principles and motivating activities in the classroom; the teacher would implement it in an effective way, and the student would experience and learn the science described in the guide.  In the real world, however, that is seldom the case.  There are many reasons for the breakdown of this ideal sequence. Curriculum planners may fall short in their planning and produce a curriculum that is in part, or in whole, impossible to implement. The teacher may be unable or unwilling to implement some, or all aspects of the curriculum.  Finally, given the range of individual differences among students, it is unrealistic to expect to design a curriculum that will meet the needs and interests of all students over the life of the curriculum guide.  As a result, teachers often find it necessary to adapt the curriculum to specific students or classes.

An official curriculum is usually contained in a curriculum guide or a written course of study. Curriculum guides range in specificity from a simple list of goals and objectives which leaves the teacher to determine teaching strategies to a highly prescriptive document specifying behavioural objectives, instructional procedures, and methods of evaluating student achievement. The trend now is away from a highly prescriptive curricula and in the direction of more general goals and objectives accompanied by suggested teaching strategies and activities.

The aim of this study is to present a guide to deliver a well designed curriculum in science (physics) that will make science more meaningful and interesting to students while relieving much of the crowding of the present curriculum. This proposal is that a central theme in the science curriculum and science content knowledge be integrated into a matrix of contextual science activities, using appropriate strategies to deal with the questions, problems and research suggested by these activities. To prepare the way for the discussion of this contextual approach, a brief history of physics teaching will be given, followed by a discussion of the components of a science curriculum. Since the attainment of scientific literacy (SL) is the aim of all science curricula, we will describe the components of SL and the accompanying components of the nature of science (NOS) .

We will begin with a brief survey of the main benchmarks of physics education since the end of the second World War. This brief survey will set the stage for discussing the requirements for any science curriculum, followed by a template for scientific literacy and the nature of science. The response of two provincial physics curricula to the PAN-Canadian science document will be given.

## A brief history of physics teaching

After the World War II, the most important objectives in designing physics curricula were:

1. Training in the *scientific method* - both for use in problem solving and in developing an "attitude in "criticalmindedness",

2. The inculcation of scientific attitudes - leading to a questioning of magic and rejection of mysticism and animism,

3. Developing an interest in the world and in socially significant problems.

There was then, and still is, a wide-spread and pervasive belief that scientists use a specifiable and teachable method in going from observation to establishing laws and theories, namely the *scientific method*. The full explication of a specifiable scientific method that guaranteed success and can be taught is rooted in Karl Pearson's picture of scientific thinking (Stinner, 1992). Pearson was a famous statistician and his understanding of scientific thinking is imbedded in a well-articulated statement of method in his influential book *The Grammar of Science*, first published in 1892. In this book he summed up the conventional wisdom of the late 19$^{th}$ century picture of the nature of the scientific enterprise. There is strong evidence that this picture of science found its way into science textbooks and versions of it were perpetuated by generations of textbook authors.

Pearson believed science was essentially an empirical-inductive enterprise that had four characteristics:

1. Science had achieved a superior kind of truth;
2. Science was characterized by inexorable progress;
3. Science was in the possession of the only method of interrogating nature, namely theempirical-inductive method (the scientific method);
4. This method could be simply described and easily taught.

Specifically, Pearson spelled out the steps of the scientific method:

1. Careful and accurate classifications of facts and observation of their correlation and their sequence;
2. The discovery of scientific laws by the aid of the creative imagination;
3. Self-criticism; the final touchstone of equal validity for all normally constituted minds.

. The scientific method, roughly as outlined by Pearson, and later enshrined and perpetuated in science texts is still with the general public and many science educators. In the physics text the author used as a fledgling high school science teacher (Eubank,1963) we find the following steps of the scientific method presented to the student:

1. There is a question or a problem;
2. Collect all the facts about the problem;
3. Propose a theory or possible explanation;
4. Test the theory with an experiment;
5. Repeat the experiment and test to find out “if it will always be true.” If not reject it.
6. If always true, it becomes a law.

It is interesting to note that “scientific law” here follows “scientific theory.”

Most scientists would agree that a complete picture of scientific enterprise that includes what scientists do on a day-to-day basis, cannot be given by the Pearsonian notion of scientific thinking. A contemporary philosopher of science, Rom Harré, sums up the wide range of activities of scientists saying that the scientists’ activities and imagination should span the discovery spectrum “ranging from informal intuitive steps to formal devices” (Harré, 1970)

According to his argument there is a spectrum of scientific involvement that ranges from identifiable mechanical procedures to high-grade activity involving the educated scientific imagination of the research scientist. This is the picture of science that we wish to present and use in this study.

The place of science in general education then was seen as important to the extent the “scientific method” could be taught. Increasing recognition of the practical, social, and social aspects of science in the curriculum was also promoted. However, the applied science tradition was criticized from two sides: The advocates of teaching the theoretical, disciplinary structure of science and the other the advocates of the humanistic cultural aspects of science.

At the time of the “Sputnik Crisis” (1957) at least three competing objectives about the nature, purposes, and emphases of school science can be identified as an activity.

1. A practical, technical, applied emphasis.
2. A liberal, generalist, and humanistic emphasis.
3. A specialist, theoretical, disciplinary emphasis.

The “Sputnik crisis” triggered a flurry of legislation and financial assistance of very high value was given to transform the science curricula in the US. The new large-scale programs later known as PSSC, BSCS, CHEMS, ESCP curricula for secondary science and SCIS for elementary science were developed. These were all heavily funded by the NSF but practical and technological applications of science were neglected. These activities in the US had a delayed, but significant effect on Canadian curriculum development.

Two theoretical structures for effective science teaching and learning were very influential in the early 1960s, namely, “inquiry learning” and “discovery learning”. These approaches were comprehensively described and effectively advocated by Joseph Schwab (*Enquiry into Enquiry*) and Jerome Bruner (*The Act of Discovery*), respectively. Schwab recommended that the teaching of science be based on understanding the “structure of disciplines”. “Discovery learning” aimed to promote thinking and reasoning skills and independent research. These two complementary programs also had a great influence in Canada in the development of science curricula in general. It was later recognized, however, that the problem with the notion of Schwab’s “structure of disciplines” was that *the material objects of knowledge* and the *theoretical objects of knowledge* were not properly separated by teachers. Michael Matthews in his comprehensive study *Science Teaching* (1995) points out that:

> *The structure of disciplines that Bruner and Schwab elevate to the forefront of science learning are structures in the theoretical objects of science: the structure of interrelating definitions and concepts contained in Newton’s Principia, the structure of geometry as contained in Euclid’s Elements, the structure of evolutionary theory of Darwin’s Origin, the structure of Bronsted’s acid/base theory or of plate tectonic theory.*

The idea is that :

> *Once these structures are grasped, then distant theorems can be derived from axioms, and predictions can be made about likely intervening species or the acidity of new chlorides, and so on.*

Matthews then goes on to say that these are not objects that are contemplated by students who first encounter the study of science.

The initially very popular “discovery learning” described by Brunner was later also recognized to be problematic because:

1. The emphasis was on the ‘processes of science’ rather than on developing conceptual frames of reference.

2. Most science teachers had never been involved in scientific research.

3. Few scientists are acquainted with the history and philosophy of science.

These curricula in the 1960’s were designed specifically to prepare students for university education. Curricular reforms aimed at more than just specifying and arbitrarily sequencing content areas. They were also concerned with attitudes and understanding of science as an activity.

James Rutherford of Harvard Project Physics and director of the AAAS Project 2061 of the early 1990s , stated the progressive view of science teaching in 1964 this way:

> *When it comes to the teaching of science it is perfectly clear where we, as science teachers, science educators, or scientists, stand: we are unalterably opposed to the rote memorization of the mere facts and minutiae of science. By contrast, we stand foursquare of the scientific method, critical thinking, the scientific attitude, the problem solving approach, the discovery method, and of special interest here, the inquiry method.*

The influential American science educator Paul Dehart Hurd lamented the failure of NSF discipline-based reforms of the 1960s to give students a sense of the broader canvas of science by saying in 1987:

> *The measure of scientific literacy is the measure of cultural awareness. The traditional science curriculum leaves students foreigners in their own culture. A problem in bringing about the essential reform of science teaching is that there are too many scientists that are scientifically illiterate and too few philosophers, sociologists, and historians of science and technology who are interested in pre-college science education*

We will discuss the notion of scientific literacy a little later.

The science curricula of the late 1970s and early 1980's began recognizing the importance the emerging research on conceptual development in science education. One discovery approach , promoted by Lawson and Karplus, was popular in the 1970s. They used Piaget's work as their basis, especially his work on cognitive disequilibrium. They asked: "How is cognitive growth generated"? The answer was: "By a process of elf-regulation and adaptation or equilibration"**.** The resolving of discrepancies in a given information to produce a self-consistent representation of this information was considered the goal of science education.

Lawson and Karplus recommended to teach by way of a three-phase model of hypothetico-deductive thinking: Exploration----invention----------discovery, that is, formal thought = hypothetico-deductive thought + propositional logic. This mode, based on classic Piagetian cognitive theory was used throughout the US for about two decades.

In the most cited Conceptual Change Model of learning in science, proposed by Strike and Posner in 1982, one mental concept is transformed into another during the process of learning, provided that the self–motivating requirements of intelligibility, plausibility, and fruitfulness are met. The Conceptual Change Model relies primarily on an analogy between the development of science as described by philosophers of science like Kuhn, Lakatos, and Toulmin, and the process of learning science, and it does not describe, in detail, any mental processes that might be involved during conceptual change**.**

What is most relevant to the classroom science teacher is their finding that for individual conceptual change or learning to take place, the following conditions must be met:

1. There must be dissatisfaction with currently held conceptions.
2. The proposed replacement conception must be intelligible.
3. The new conception must be initially plausible.
4. The new conception must be fruitful and diversely connected, that is, it must offer solutions to old problems and to novel ones.

Michael Matthews, in his, says:

*The problem for constructivists is how, given their principles, to get children to believe, understand, understand and make meaningful scientific ideas that not only transcend their experience, but are often in outright contradiction with their experience.*

Matthews goes on to say that :

*Some have likened learning science to learning a foreign language: there is an awful lot that just has to be learnt before the totality begins to make sense, and before one can be a critical user of the language.*

In conclusion, science educators generally believe that first of all science teachers must *identify*, *respect* and then *'built upon'* students preconceptions and, secondly, are aware of the four conditions of conceptual change listed above. Finally, it is important for teachers to realize that when they are confronted by a class of 25 students teaching a concept like force, there will not by 25 different conceptualizations of force, but only about 4 or 5. Clusters of students' preconceptions of main concepts have been identified and catalogued by researchers for motion, forces, heat, electricity; in the very comprehensive work by Driver at all.

Teachers' awareness and knowledge of how students learn will not only involve a change of teaching methods, but are more likely to bring about a revolution in classroom culture, including the roles of teachers and students as well as the course goals (Wubbels & Brekelmans, 1997). A constructivist innovative teaching program normally implies modification of teaching tasks/strategies, learning tasks/strategies, and criteria of learning achievements. Thus, the teachers' role shifts from knowledge provider to learning facilitator, and that the student's role shifts from information collector to active practitioner (Hewson & Thorley, 1989; Roth, McRobbie, Lucas & Boutonne, 1997). In addition, the foci of learning achievement may be broadened from mere knowledge accumulation to personal development, including attitudes of learning and adoption of learning strategies (Cross & Angelo, 1992; Donald, 1993; Elby, 1999; Elb).

**The science curriculum**

Every science curriculum has at least four parts (either explicitly or implicitly stated):

1) A theory about the nature of science;

2) A rationale for the distribution of scientific knowledge, with tacit assumptions about the learning process;

3) An assumption about how scientific knowledge relates to other knowledge, particularly to the humanities; and

4) A concern with the relationship among science technology and society

The Pan-Canadian document for setting a template for science curricula recognizes that effective teaching toward SL presupposes that science teachers have a good understanding of the nature of science. Recent reviews of the research, however, clearly show that science teachers generally do not possess adequate conceptions of the nature of science. The general recommendations of these findings are that courses in the history and philosophy of science should be included in teacher preparation programs. Can we achieve this promise?

**Physics and Scientific Literacy**

In Canada, the Pan-Canadian Science Education document, drafted in the middle 1990s by participants from all provinces, provides a framework for local and provincial curriculum developers in science education. The framework is guided by the vision that "all Canadian students, regardless of gender or cultural background, will have an opportunity to develop scientific literacy". The objectives of this proposal are to develop new conceptual and methodological perspectives in science education and promote scientific literacy (SL) in a more humanistic manner. These perspectives include the development of science stories, historical case studies, contextual settings, scientific narratives, and thematic approaches to help science teachers become more effective in the science classroom. In addition, the project is designed to promote a cross-disciplinary approach to science education and to initiate collaborations and dissemination of knowledge at the international, national, and local levels in a unique and innovative partnership We will look at two physics curricula later, to see how diversely the provinces have responded to the guidance of the PAN - Canadian science document

A quick review of the literature on SL surveys in the United States, Canada and in Europe , however, will show that even the most optimistic estimates of SL levels among the general public do not rise above 10 per cent. Science educators have placed the blame on the predominantly textbook-centered teaching taking place in science classrooms that encourages memorization of "scientific facts" and promotes the often mindless recitation of algorithms. The problem of diminishing interest in science must also be connected to the students' perceived irrelevance of the content-driven and decontextualized science teaching they encounter in the majority of their classes.

Most science educators recognize that innovative approaches are needed in science education if we want to raise the general level of SL significantly. There is strong evidence that we must strive to connect cognitive activity to context and a story-line: Teaching methods imbedded in contexts and stories are not merely useful, they are essential to conceptual development. Moreover, historical and philosophical contexts assist in the development of students' understanding of the nature of science and promote critical thinking.

It is now commonplace to say that in order to be effective in the classroom, science teachers (indeed, all teachers) require to have good content knowledge as well as pedagogical content knowledge of their subject. To possess the first is regarded as a necessary but not sufficient condition for successful teaching: teachers must also be well acquainted with good pedagogical practices in general and have a thorough understanding of how students learn the concepts presented to them in particular. The possession of content knowledge presupposes a period of formal training in that subject, usually a minimum of a three year general degree at the university level. To complete the requirements for the future a science teacher it is assumed that he/she has been exposed to and participated in learning about ways of applying sound pedagogical principles and what cognitive theories say about how students learn. This usually takes another two years of studying at a Faculty of Education. To sum up: the new science teacher should be 1. Scientifically literate 2. Understand the nature of science 3. Have a good understanding of cognitive theories and what they say about how students learn

To be scientifically literate on the level of a science teacher presupposes content knowledge of the subject as well as an understanding of the NOS. An understanding of the NOS, in turn, assumes more than a cursory knowledge of the history of science.

**Scientific Literacy and the Nature of Science**

The following are components of SL which are relevant to this study. While every curriculum project emphasizes the centrality of SL in the teaching of science, there is no one widely accepted set of components for SL. Since an important part of SL is the understanding of NOS, a scientifically literate person is presupposed to have a good understanding of NOS. A Template for Scientific Literacy given below.

**A Template for Scientific Literacy:**

A scientific literate person is expected to, among other things, to:

1. Understand fundamental concepts, laws, principles, and facts in the basic sciences.
2. Appreciate the variety of scientific methodologies, attitudes and dispositions, and appropriately utilize them.
3. Connect scientific theory to everyday life and recognize chemical, physical and biological processes in the world around them.
4. Recognize the manifold ways that science and its related technology interact with economics, culture and politics of society.
5. Has developed science-related skills that enable him or her to function effectively in careers, leisure activities, and other roles;
6. Has developed interests that will lead to a richer and more satisfying life and one that will include science and life-long learning.
7. Understands significant parts of the history of science, and the ways in which it has shaped, and in turn has been shaped by, cultural, moral and religious forces.

The following is a list of what the possession of an adequate knowledge of the nature (NOS) of science entails. These are selected statements which in my opinion are fundamentally relevant to the discussion in this presentation.

***A Template for the Nature of Science***

1. There is an “objective” external world, independent of the existence of an observer.
2. Scientists operate on the belief that there are regularities and structures in nature that can be discovered by careful, systematic study.
3. The “objectivity “ of science depends on inter-subjective consensus and validation by the community of scientist that work in a particular field of investigation.
4. Scientific theories, are “nets” that contain laws, principles, definitions, and rules of inference that allow us to “catch” the phenomena of the world.
5. These theories guide our thinking and determine what is a “scientific fact”.
6. Scientific knowledge, including theories, is tentative and should never be equated with truth. It has only temporary status, albeit often a long one.
7. There can be no sharp distinction made between observation and inference.
8. There is no one specifiable scientific method that can be taught and guarantees success in all scientific investigations.
9. There are different traditions in science about what is investigated and the methodology used, but they all have in common certain basic beliefs about the value of evidence, logic, and good arguments.
10. The methods of science are limited to the physical world

**Scientific literacy and physics literacy.**

Basic scientific literacy (SL) is supposed to be an achievable goal for all our students by the time they complete high school. Those students who complete high school have at least obtained credit in science on the grade 10 level and many have completed at least one course in physics, biology and in chemistry. Of those who successfully complete two courses in physics, chemistry and biology on the grade twelve level the majority will continue their studies in science, engineering, or medical sciences (Rigden, 1991).

We have seen that there is no universally agreed upon definition of SL. Most conventional descriptions, however, involve a certain number of skills, an understanding of science processes and science content, an appreciation of science and technology-all leading to the ability to make wise career choices and informed judgement about scientific and technological research and personal health. However, I think that most science educators would agree that no matter how we define SL it must include a rudimentary knowledge of physics. I would like to argue that an elementary understanding of basic physics must be seen as a necessary but not sufficient part of background knowledge of a scientifically literate person.

First, physics is thought to be the science that has been developed to the highest level of quantitative and theoretical sophistication. Secondly, the fundamental problems we find in all sciences, such as the question of how we construct theories, the nature of explanation and how it is related to prediction, and the question of how science progresses in general, were originally discussed in the context of physics. Finally, physics is considered fundamental, but not reducible to other physical sciences, such as chemistry and to a certain extent biology.

The picture of physics taking a central position in educating toward SL would suggest that if we want to establish a good base for scientific literacy students must encounter the conceptual schemes of physics at a much earlier age than grade 11. In many European countries (England, Germany, Denmark) physics is taught as early as grade 8, and in some countries as early as grade 6. In England all students now must study physics to the GCSE level at age 16 (grade 10). That means that all students will have had instruction in physics for three years. In Canada, on the other hand, students encounter physics in the lower grades but only in small units. Manitoban students, for example, learn some physics directly in short core units usually called Force and Motion, Machines, Heat, as well as in such optional units as Flight, Earthquakes and Earth in Space.

My observations as faculty of education consultant, however, suggests that the physics in these units is mostly taught by way of memorization of facts and the recitation of simple algorithms (definition of density, definition of mechanical advantage and the law of levers, Newton's second law, Ohm's law- combined with the solving corresponding simple "type problems"). Knowledge of scientific facts, of course , is important. It is equally important, however, for students to make connection with experiential and intuitive ideas that lead to a good understanding of the evidential and theoretical background in which those facts are imbedded.

As the physicist Anthony P. French, referring to the teaching of physics, has pointed out, “the problem of reaching the average student remains unsolved, and even among the academically talented, scientific literacy is the exception” (French, 1986).

**What does research in cognitive science tell us about teaching science?**

Even a brief glance at the journal article titles since the late 1980’s will show that the ideas of constructivist learning theories have dominated science education research. There is, of course, a long lag time between the research done in science education and the implementation of the findings of this research into curricula and classroom teaching.

Piaget thought that we make sense of the physical world by content-independent logical structures and operations. Modern constructivists, however, believe that domain-specific knowledge schemes are important and not general reasoning schemes. It is important for science teachers to realize that Piaget was a cognitive scientist and his findings do not constitute a “learning theory”.

Science teachers should know and discuss the basic assumptions of constructivism. These are easily stated:

1. Kowledge is actively constructed by the individual. .

2. Coming to know is an adaptive process that organizes one’s experiential world; it does not discover an independent, pre-existing world outside the mind of the knower.

The degree to which these are taken, determines where on the spectrum one is.

Moreover, research shows that:

1. Learning is experience-based, context-bound and domain-specific.

2. Learning is an adaptive process in which the learners’ conceptual schemes are progressively reconstructed in keeping with a wider range of

experiences.

3. Learning is dependent on the preconceptions that learner brings to the educational experience.

4. Learning is highly dependent on the context in which it occurs.

5. Each learner must construct his or her own meaning.

In addition, we must pay attention to the key findings of research in conceptual change in science. that common sense ideas and preconceptions are persistent and often stay with a student into studies at the university level.

# Chapter 2

## The Notion of Evidence in Scientific Inquiry

(Note: This chapter should be read while studying the LEP model power point)

What reasons do we have for believing that..?

The notion of evidence in science

The logical plane of activity

The evidential plane of activity

The psychological plane of activity

The Theory-Evidence-Psychology Connection

The LEP model of concept development

One of the main questions scientists are concerned with is the relationship between theory and evidence. Clark Gilmour, a contemporary philosopher of science says that a great deal of the fascination we have for science "*derives from the delicacy and the ingenuity with which scientific practitioners attempt to establish the relevancy of some bit of evidence to some bit of theory*". He goes on to say, "*My belief is that many of the features of scientific method, and the grounds for many methodological truisms, derive from features of a general strategy commonly used to establish the relevance of evidence to theory*". (Gilmour, 1980).

### The Notion of Evidence in Science

Perhaps the best way to begin our investigation of the often neglected the relationship between evidence and theory is by looking at examples of scientific reasoning.

**Example 1**: You are discussing with a friend the relationship between diet and heart disease. You make the following claim,

"Vegetarians live longer because they have a lower cholesterol level in their blood and therefore a lower incidence of heart disease". Your friend would immediately respond with, "What evidence do you have for this claim?" Depending on your background knowledge you might offer a reply ranging from appeal to authority to a detailed statistical analysis to a biochemical explanation of the underlying mechanism involved.

**Example 2**: Imagine that a physician is faced with the problem of tracking down the cause of an outbreak of food poisoning. After some inquiry and reflection the physician claims that the food poisoning was caused by eating chicken. What evidence did he have for making this claim? This was his argument: all the patients had the symptoms that he recognized as those of salmonella. Moreover, every victim ate at the same restaurant at the same time, namely dinner. Finally, he found out that those who did not experience the symptoms shared everything the victims ate and drank except chicken. His conclusion that the chicken caused the food poisoning followed. Most people would follow this evidential argument and probably agree with it.

**Example 3**: A physics student and his friend, while visiting an old fort, look down of a deep well. They cannot see the bottom of the well.The physics student turns to his friend and says, "This well is approximately 32 meters deep, give or take a meter." His friend replies, "How do you know that? Did you read it in the brochure?" The physics student smiles and says, "No, I was here earlier and timed the fall of a heavy rock. Based on that information I quickly calculated the depth of the well". His friend, who had not yet taken physics but was a good maths student looked puzzled and then asked the physics student, "How did you find the time of fall, you cannot see the splash!" The physics student smiled, "Last semester we solved a problem like this in class. Knowing the speed of sound at a given temperature you can set up two simultaneous equations, one involving free fall and the other involving the speed of sound. I kept the algebraic solution in my calculator". He proceeds to drop a stone, measures the combined time it takes for the stone to fall and the time it takes for the sound to return, pulls out his calculator, punches in the numbers for total time, temperature, and local gravity, and says, "Yes, about 32 meters."

**Example 4**: The science teacher is discussing the composition of the sun's atmosphere. She says, "One of the gases in the sun's atmosphere is Helium". Then she adds, "You may be interested to know that Helium was discovered in the sun's atmosphere before it was discovered on earth". One bright student wants know what the evidence is for believing that there is Helium in the sun. Another student is puzzled about how it is possible to identify an element in space before it was found on earth.

The science teacher tells the students that when such elements as Hydrogen and Helium (they are in gaseous form) are contained in a glass tubing at low pressure and exposed to a high voltage they leave a characteristic signature on a spectrograph. She shows the spectrograph of Helium to the students. Then she shows a spectrograph of the sun's atmosphere. The students are suitably impressed and still somewhat puzzled.

**Example 5**: In a grade nine class the discussion centres around the Bohr atom. Students are told that all atoms except hydrogen are made up of protons, electrons and neutrons. The teacher says, "Hydrogen is the simplest of the elements. An atom of hydrogen contains a positively charged proton in the centre with a negatively charged electron circling the proton". One student responds, "How do you know that there are protons and electrons?" Another student wants to know what evidence there is for thinking that the electron revolves around the proton. The class science whiz presses the teacher to explain why the electron does not fall into the proton. The teacher will have a difficult time mounting an evidential argument that "makes sense" and is appropriate to the level of grade nine students. She might use terms like "model", "theory" and "hypothesis", but most students will simply memorize the knowledge claim without feeling a need to have appropriate evidence.

Notice that in each of the above five cases:

1. A claim was made of the form: "I know that...". We will call such claims *knowledge claims.*

2. Support was found for that knowledge claim. We will call this support ***evidence*.**

3. Background experience and knowledge was available. We will call this *theoretical background or knowledge background.*

4. An appropriate argument was given that connected the knowledge claim with the evidence by way of the theoretical background. We will call this way of arguing an *evidential argument.*

5. A selection process is involved in supporting a knowledge claim <u>and</u> in deciding the adequacy of the evidence. This selection process as well as the adequacy of the evidence depends on the background knowledge as well as on the skill of the knowledge claimer at presenting an appropriate argument. The more extensive this background knowledge is and the more experience one has in presenting evidential arguments the more guarded will be the selection process and the more intricate the argument presented.

These examples then suggest that evidence is only meaningful if it is supported by a background knowledge. Moreover, this support must be based on an appropriate argument given and understood by the person who makes the *knowledge claim.* Therefore, the selection of evidence (and the decision of the adequacy of this evidence) depends on the background knowledge of the <u>knowledge claimer</u> as well as his/her experience in presenting an appropriate argument. Let us look at each example again in terms of these five features. (see Figure 3)

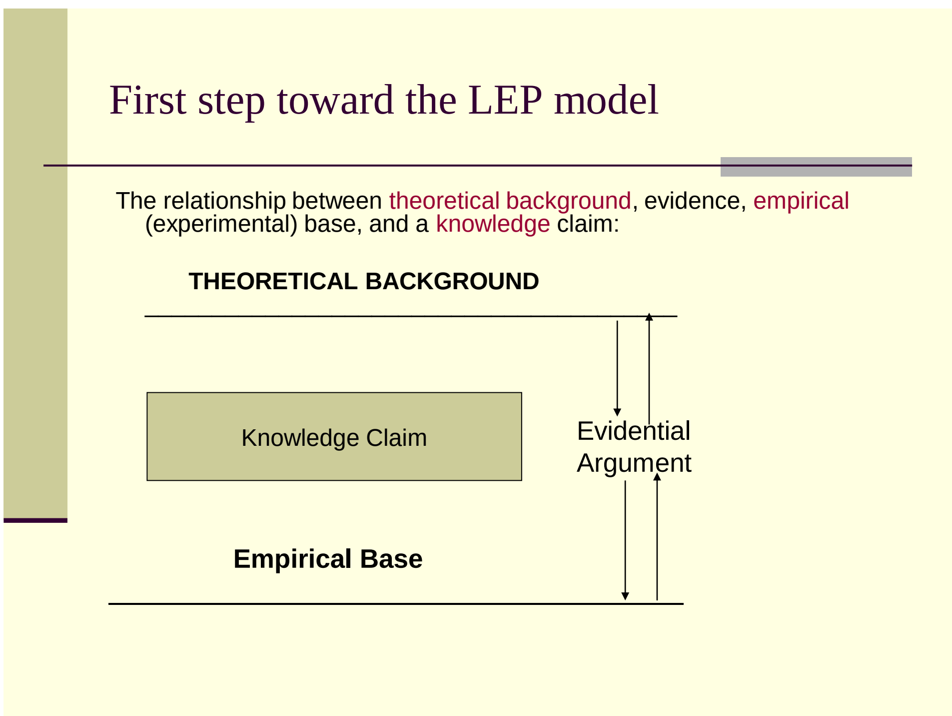

**Figure 3** The relationship between theoretical background,

evidence, empirical base and knowledge claim

Let us briefly review each case. In the first example the <u>knowledge claim</u> is, "Lowering the cholesterol level lowers one's risk of heart disease". The <u>evidence</u> is of a statistical nature and of an explanatory nature that refers to an extensive background knowledge.

The relationship between theoretical background, evidence, empirical (experimental) base, and a knowledge claim:

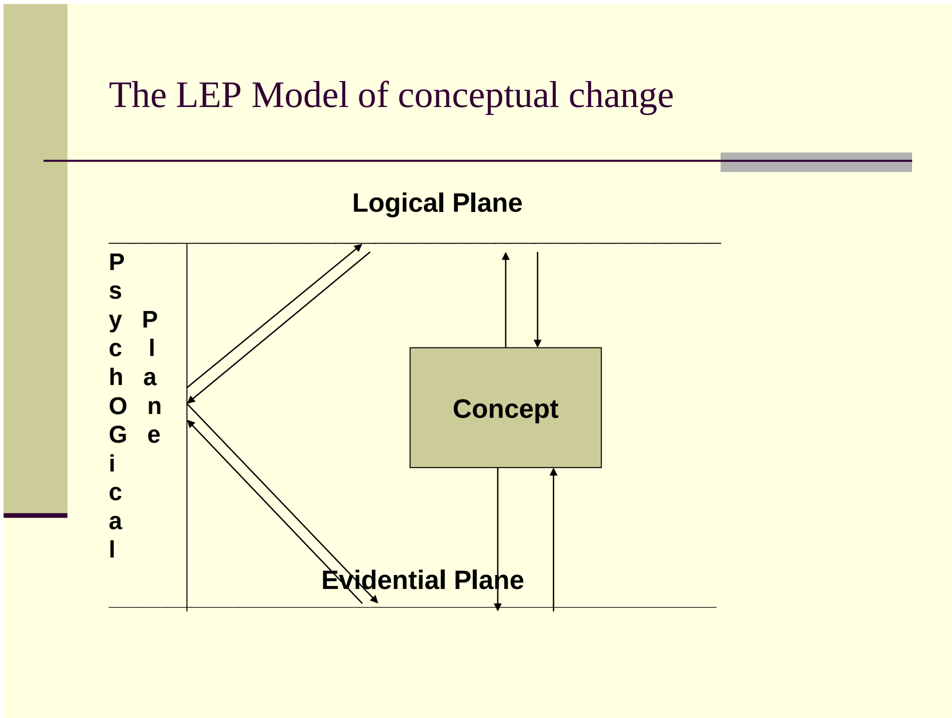


**Figure 4** The psychological plane bridges the evidential and logical planes.

The background knowledge might include knowledge of the relationship between fat intake and cholesterol production, the role of cholesterol in the body, the statistical evidence for relating incidence of heart disease and cholesterol level as well as to importance of the ratio of HDL and LDL, the mechanism of platelet deposition in the arteries, the effect of taking an aspirin a day on this deposition, the relationship between exercise and cholesterol level, the relative frequency of physical exercise of vegetarians and meat-eaters, etc.

The nature of the evidence presented will depend on the background knowledge of the knowledge claimer. For example, he/she might stress the statistical evidence without considering the underlying mechanism of platelet deposition. Or he/she might discuss the latest hypotheses of the underlying mechanism that relates cholesterol level and platelet formation. Of course, one might simply quote a recognized authority and not attempt to argue at all. The challenge here for the expert knowledge claimer is to select evidence that "makes sense" and is seen as adequate evidence.

In the second example the knowledge claim is, "The cause of food poisoning in this case is the eating of chicken". The evidence is based on recognizing symptoms of salmonella, confirming that indeed only those who ate the chicken were stricken. The background knowledge includes the experience of the physician with the symptoms of salmonella, knowledge of the circumstances that connects only those people who became sick to the eating of chicken. The argument presented is based on a process of elimination (a form of inductive reasoning) and on experience in recognizing the symptoms of a disease (a form of deductive reasoning).

The third example is typical of how students reason in elementary physics. The knowledge claim here is, "The depth of the well is 42 meters". To be sure, the average high school physics student seldom applies his knowledge of physics outside the classroom. However, what makes this claim remarkable is that the student firmly believes that he is right even though he did not directly measure the depth. His evidence is based on one indirect measurement, namely the time it took to hear the splash measured from the moment of releasing the stone. The background knowledge, however, has to be fairly extensive. He has to be able to manipulate the equations of elementary kinematics and know the algebraic technique associated with quadratic equations. Moreover, he must be able to recognize the problem situation as one that is similar to the one they solved in class. This kind of problem solving is called an algorithm, involving a set of finite steps that lead to the correct solution. The argument then involves the identification of the relevant data (in this case the time that elapsed, and the temperature of the air) and the recognition of the correct formula or algorithm that will solve for the quantity sought. This kind of argument is deductive in some sense of deductive (see chapter III).

You should notice that the friend who does not have the background in physics will simply have to accept the evidential argument and defer to authority. What would the physics student say if he were asked why he has such confidence in his calculations even though he had never actually checked such results "in the real world?"

In the fourth example our knowledge claim is, "The sun's atmosphere contains Helium". The background knowledge includes the physics of electromagnetic radiation, quantum mechanics and the principles of spectroscopy. The evidence to support that claim is primarily based on spectrographic analysis of the light that comes from the sun. Physicists match the emission lines in the solar spectrograph with the emission lines of Helium from a discharge tube. The match is exact and for most students this would be a sufficient evidential argument for supporting the claim that there is Helium in the sun. However, a complete evidential argument would need to consider such topics as emission and absorption spectra and the theory of energy production in stars.

The background knowledge that is required to present a complete evidential argument is very extensive. One would have to be acquainted with the physics of electromagnetic radiation, quantum mechanics, and the principles of spectroscopy. The argument here would take the form of a deductive argument.

In the fifth example the knowledge claim is, "The hydrogen atom is made up of a proton and an electron, with the electron revolving around the proton". The evidence here is based on the mathematical formulation of the Bohr model making connection with the emission spectrum of the hydrogen atom. The background knowledge is to be found in the mathematical model that uses classical arguments from electromagnetic theory and Newtonian mechanics and combines them with ideas borrowed from Planck's quantum mechanics. Moreover, Bohr's model must also make connections to such classic experiments as Thompson's determination of the e/m ratio of the electron, Rutherford's gold foil experiment and Millikan's determination of the charge of the electron. How can we present to a grade nine science class an appropriate evidential argument for the above knowledge claim in the light of this high-grade theoretical background?

This brief discussion of the notion of evidence will serve as a preamble for a larger discussion of how scientists use evidence to arrive at a theory that determines how they "see" the world.

***How Scientists Look at Evidence When Establishing a Theory***

The "big" theories of science: Newton's gravitational theory, Darwin's theory of evolution, kinetic molecular theory of gases, Mendeleev's periodic arrangement of the elements, Wegener's continental drift theory, Bohr's theory of the atom, Planck's quantum theory, Einstein's theory of relativity, are not established by the conscious application of a specifiable scientific method. We arguedearlier that historians of science and philosophers of science are generally agreed that such theories are not arrived at by way of a specifiable inductive procedure. Rather, they are the product of scientific imagination based on a set of presuppositions (which are not directly testable), previous theories, questions, experiments, deciding what counts as evidence, and lucky guesses.

A high-order theory like Newton's theory of gravitation is not based on systematic analysis of data (although at times data is systematically analyzed). Such a theory should be seen as the sum total of the answers we obtain to our ordered questioning and our selection of evidence, sometimes expressed in a compressed series of mathematical and definitional statements. Moreover, the question-and-answer procedure involves experiments, generates problems that must be solved, often using evidence that is selected on the basis of an incomplete theoretical background. The struggle to achieve a conceptual basis for such a theory involves a continual ordering and re-ordering of questions in response to experimental results. Moreover, what counts as evidence changes with the evolution of the theory.

***Implications For Science Teaching***

We have established some of the basic principles of how to relate evidence to theory. We can use these principles in planning our teaching of concepts and topics in science. We can also map out the evolution of the "big" theories of science.

Using our brief discussion of background knowledge and appropriate evidential argument for the examples as a guide we should be able to plan our teaching strategy for topics and concepts. We can also tackle the more difficult task of giving the student an adequate and appropriate evidential basis for the "big" theories, roughly along the lines suggested above. The complete strategy for giving the student adequate and appropriate evidential basis.

## The Theory-Evidence-Psychology Connection

As science educators in a scientific age we are facing the following problem:

*On the one hand we have available a wide spectrum of textbooks, a proliferation of support scientific literature, modern laboratory equipment, computer-aided interactive programs, and excellent media programs. On the other, we face disinterested, bored, overburdened students who do not find the study of general science in the middle years exciting, or the study of physics or chemistry in high school and in college an intellectual adventure*.

In junior high schools, too, teachers find that students are frequently "turned off" science. This is not surprising when one considers that they are routinely asked to perform tasks on the basis of a theoretical model that is not connected to an *evidential-experiential* base that "makes sense". Solving problems based on a memorization of *Ohm's law*, or memorizing the *valences* of elements in order to balance chemical equations are good examples of such tasks. At the high school level the problem becomes more acute because textbook-centered teaching is almost exclusively an algorithm-recitation process.

It is commonly known, however, that science teaching is generally textbook-centered (Renner, J. *et al*). Consequently teaching takes place chiefly on, what we shall call, the *logical plane* (mathematical-algorithmic-factual), with only occasional tentative excursions to what we shall refer to as the *evidential plane* (experiential-experimental- intuitive).

How then should we approach the teaching of science in general in view of what we have said? Most successful science teachers argue for frequent contact with the *evidential plane* in the teaching of physics. However, they assume that this is a straight-forward pedagogical task.

One of the reasons for the failure of science teaching to help students make contact with appropriate evidence may be science teachers' inadequate background knowledge. However, another important reason must be the insufficient attention given to the question of how students learn science concepts.

The general pedagogy of the classroom teacher seldom include, nor do textbooks discuss, the third plane of activity, namely the *psychological plane*. This plane involves the activities related to how students learn concepts in science. Textbooks, of course, leave the pedagogy, or the question of how students learn science, to the science teacher.

We will make the assertion that in planning successful science teaching we would need to pay attention to all three planes of activity, the *logical*, the *evidential*, and the *psychological*. We have already discussed the theory-evidence connection of science and science learning in the last chapter. We will now add the psychology connection, after a brief description of the three planes of activity.

***The Logical Plane***

On this plane of activity we encounter the finished products of a science, what we called in the previous chapter the background theory, such as laws, principles, models, theories, and "facts". The basic question on this plane is, "What operation(s) will link the conception to the evidential plane?" because this determines to what extent the activity on the *logical* plane relates to the *evidential* plane. (See Figure 4)

The concepts of density, valence, and specific heat, Newton's second law, F= ma, the principle of conservation of energy, the Bohr model of the atom, the *kinetic-molecular theory of gases* and the "scientific fact" that the electron is the basic electric charge, are found on this plane.

The following examples, one taken from each of, physics, chemistry, and biology respectively are good illustrations of the textbook's major preoccupation with the *logical*

*plane*. These are:

a. in physics, the mathematical formulations of *Newton's second law of motion* (usually first taught in grade 11);

b. in chemistry, the *rules for chemical combination* based on the notion of *valence* of the elements (often first taught as early as grade eight); and

c. in biology, the *circulation of the blood* (also often first taught in grade eight or even before).

Newton's *second law of motion* is usually given as fully developed mathematical formulation often supported only by a teacher generated demonstration. The cognitive linkage between the formal abstraction and the the data generated by the demonstration is seldom clearly established. The student is left with a memorized verbalization. Experimental activity, if any, is of the "to verify Newton's second law" type. Students then solve a host of problems from the textbook dealing with motion and forces by applying algorithms.

In the chemistry example a definition of *valence* as "combining power" is given and the algorithm for combining such elements as oxygen and hydrogen are laid out. The explanation of valence is usually wrongly given in terms of the Bohr model of the atom, and students are taught to relate the number of outer shell electrons with valence. The Bohr model then is supposed to be the evidential connection for the rules of combining elements. This topic is usually discussed in grade 11 chemistry in this fashion, but unfortunately it is often taken up in detail as early as in grade eight.

The *circulation of the blood* is usually discussed in grade eight. Students memorize "scientific facts" from diagrams and descriptions in the text. An operational definition, if one is given at all, will refer to pumps and "closed systems". Sometimes teachers may show large scale models of the circulatory system. Students memorize a host of "facts" and study schematics depicting the circulation of the blood. Students must accept, on faith, that the blood circulates throughout the body.

***The Evidential Plane***

On this plane of activity we encounter the experimental, intuitive, experiential connections that support what we accumulated on the *logical plane*. We saw in the previous chapter that the first question we should ask on this plane are, "*What are good reasons for believing that*...?" Here we are looking for evidence that "makes sense" to the student. The second question we should ask is, "What are the diverse connections of this concept?" Here we wish to show that the concept is valid when used in seemingly disparate areas in scientific inquiry.

Thus, when presenting the topic of motion and forces, essentially Newton's second law, we should provide the students with opportunities to consider every-day examples of motion. This should be done in response to such questions as, "What are good reasons for believing that only an unbalanced force acting on an object produces an acceleration?" In response to this question simple experiments should be designed, sometimes initiated by the teacher but more often by the student. The typical textbook experiments of the kind "To verify Newton's second law" should be avoided. We should also delay the presentation of the finished product of the mathematical formulation of Newton's laws, such as F = m x a. Before presenting these "formulas", however, the teacher should consider the question, "What are the diverse connections that led Newton's to his second law?" It turns out that there were three empirical connections: the motion of the pendulum, the results of collisions between hardwood balls attached to two pendula, and the motion of the conical pendulum.

These seemingly disparate phenomena were finally united conceptually by essentially one equation. In other words, the results of these experiments plus the scientific imagination of a Newton produced the equation of motion F= ma. Of course, it is not suggested that we should attempt to recapitulate high-grade scientific thinking when we are working on the *evidential plane*. However, discussing the evidential basis for the finished mathematical product, such as F= ma, as a splendid science story, can be very motivating as well as illuminating.

The concept of *valence* is taught to students by introducing *ad hoc* rules for writing simple compounds, such as HCl and $H_2O$. This is done without any evidential basis other than the appeal to the simplified Bohr model of the atom. Students respond to this kind of "evidence" with questions that can always be translated to mean, *Why should I believe this? or provide me with good reasons for believing*...Unfortunately, most science teachers' stock response here would be, "Hydrogen has one electron in the outer shell and therefore has a valence of +1 and Chlorine has seven electrons in the outer shell therefore has a valence of -1 ..." Junior high school students simply do not see the model of the Bohr atom as properly placed on the evidential plane. Students respond with confusion and ultimately with boredom.

Again, as in the case of our example from physics, a historical approach is appropriate. The concept of valence was well established and *diversely connected*, long before Bohr's model of the atom was established in 1913. Originally the "combining power" of elements was connected to the two cornerstones of chemistry, the law of conservation of mass, and the law of definite proportions. Simple experiments, such as the *electrolysis of water*, a demonstration of the chemical combining weights of sulphur and iron, should be devised for students to illustrate these laws. On the basis of such experiments, and on a clear (pre-Bohr atom) understanding of the concepts of element and compound only should the students proceed to write the formulas of simple compounds.

The *circulation of the blood* is studied almost exclusively by memorizing "facts" and schemata from textbooks. The questions one asks on this plane are generally not answered to the satisfaction of the student. For example, little or no attempt is made to recapitulate Harvey's original arguments of why the blood must circulate. Thus the opportunity to involve the student in one of the first "thought experiments" in biology is missed.

A common misunderstanding is that *thought experiments* are highly theoretical and abstract. However, students find the classic thought experiments of physics often more compelling than concrete demonstrations. Harvey's thought experiment to "prove" that the blood must circulate is no exception (Stinner, 1990).

### ***The Psychological Plane***

In this plane we pay attention to the students' pre-scientific knowledge, and to their previous school science. Here we study the responses they have to some key questions we shall pose in testing their readiness to accommodate a concept. Textbooks generally are not directly concerned with the questions we must ask on this plane. It follows that most science teachers engaged in textbook-centered teaching pay little or no attention to how students' preconceptions interact with what is being taught.

The three key questions we will use in making connections between the *evidential plane* and the *logical plane* are based on the work of Posner *et al* (Posner, 1982) and partly on suggestions made regarding the phrasing of subsidiary questions by Hewson *et al* ( Hewson, 1989) (See Fig. 1). The first question sets the necessary precondition for a concept to be considered at all as a candidate for assimilation or accommodation: the student must find a concept intelligible before any meaningful teaching can take place. For example, a student may not find the mathematical formulation of Newton' second law, namely F= ma intelligible, i.e. he/she cannot solve problems involving F= ma consistently without using a *mnemonic* and without slavishly following an algorithm. Therefore if the first question cannot be answered with certainty we cannot proceed to the second question which sets the stage for establishing *plausibility.* The student then cannot go beyond meaningless algorithm-recitation on the *logical plane,* since a connection with the *evidential plane* is not possible.

In the chemistry example involving the concept of *valence* teachers encounter similar hurdles. Students in a grade eight class often find the Bohr model not intelligible, i.e. they simply may not be able to connect consistently the electron state of the outer orbit with the "combining power" of the element when writing chemical formulae. As in the case of F = m x a, the student (and often with the full consent of the teacher) must resort to memorizing a *mnemonic*. Students also may find the Bohr model not *plausible.* After all, they have no evidential basis for believing in such a model.

The *circulation of the blood* as a concept is found to be intelligible and plausible by most students, especially after a discussion of Harvey's arguments. In the experience of the writer it is always astounding to see the delight on the faces of fledgling science teachers when first exposed to Harvey's simple but compelling thought experiment.

Ideally, of course, one wishes to see every concept carried through to satisfying the requirements of the third question, that of *fruitfulness.* In the physics example, that would mean being able to answer questions about how Newton connected his mathematical formulation of laws with the available experimental evidence. In the chemistry example, that might involve the student consciously trying to understand such phenomena as *electrolysis and electroplating*, and how experimental evidence suggests the concepts of *electrovalence* and *covalence*. Finally, in the biology example, the student might want to know how diseases spread throughout the body, what the underlying causes of heart attacks and strokes are, etc.

Only when students can see new connections, perceive a variety of possibilities, and come up with new ideas, is a concept fully accommodated.

## Summary and Conclusions

We laid out the three planes of activity, the *logical,* the *evidential,* and the *psychological.* To illustrate how these planes are connected we used three commonly taught science topics (two in junior high school and one in senior high school). The three planes of activity were then related by way of the scientific concept.

The modest expectation of this approach is that teachers reflect on the concept they are about to teach, its place, origin, and its relationship to the theoretical background. This reflection should encourage them to collect appropriate evidence that "makes sense" to the student, in answer to the questions, "what are good reasons for believing that..?." and to " what are the diverse connections of the concept?" Finally, it is hoped that teachers would map out the many connections between the activities on the *evidential* and the *logical planes*, filtered through the requirements demanded by the questions on the *psychological plane.*

A large number of publications recently have explored teachers' understanding of the nature of science (Selley, 1989, Martin 1990, Collins 1989, Abell 1989, Davson-Galle 1989, Akeroyd 1989) as well as efforts made to help teachers understand the nature of science (Arons 1989, Rohrlich, 1989, Jordan 1989). Moreover, there is a vigorous attempt on an international level to explore ways to introduce the history and the philosophy of science into science teaching (Brush, 1989; Cushing, 1989; Kenealy, 1989, Matthews, 1989)

A recurrent complaint of these papers is that most teachers perceive science as an empirical-inductive enterprise. This is not surprising, since most textbooks implicitly or explicitly support this picture of science ( Selley, 1989). There are, however, difficulties in instituting programs that would involve a philosophical orientation in the preparation of science teachers. One of these difficulties is connected with the question of which of the well-known philosophical views (Popper, Lakatos, Toulmin) one should use (Martin *et al*, 1990).

Perhaps a modest start could be made to take teachers beyond a simplistic understanding of science as an empirical-inductive enterprise. This could be accomplished by having teachers frequently and habitually consider the three planes of activity as outlined here. When using the model, teachers should consult diverse texts and other sources that deal with historical contexts and philosophical issues of science. Science teachers should also collaborate with their colleagues on an on-going basis in finding new and fresh evidential material. Implicit in this approach, for example, will be the need to clarify relationship between *experiment, hypothesis* and *theory* in scientific inquiry. The use of the model as a *heuristic* device then would allow an *eclectic* discussion of philosophical issues that would be independent of a school of thought. Moreover, repeated excursions into historical background will surely generate interest for the teacher and the student alike.

Indeed, one of the strengths of making contact with the evidential plane is that it inevitably draws us into a historical consideration of the origin of a concept. This was the case with each of the examples we discussed, Newton's second law of motion in physics, the concept of valence in chemistry, and the notion of circulation of the blood in biology. In each case the teacher would be forced to research the historical contexts to provide appropriate evidence for what the students is given on the *logical* plane. This kind of activity and reflection would reeducate the teacher and change his/her view and understanding of science. In fact, one could claim, that using this approach "science teachers are being challenged to present science as it 'really is, rather than promote a mythic, textbook science" (Martin *et al*, 1990).

The textbook will probably be with us for some time to come. It may even be *necessary* for the education of the scientist, as some writers seem to believe (Brackenridge, 1989). Textbook-centered teaching, however, is not *sufficient* in producing the scientist "who will easily discover a fresh approach" or educate the layman who will be scientifically literate. To achieve that, science teachers must recognize as well as understand the two-way passage from the *logical* plane to the *evidential* plane. Recognition and understanding of this passage by textbook writers may change the format and the role of textbooks in the future.

The following activities in high school science are typical examples of topics that are often taught as rule-memorization (what we called algorithm-recitation). The activity that allows the student to solve successfully such problems often becomes just that, a purely puzzle-solving activity. When students solve these problems they are working on the logical plane. Working on the logical plane is fine but not if it is disconnected from the evidential plane in the experience of the student.

Thus students are able to balance equations, solve problems of free fall, etc., without a firm understanding of the concept of valence, or the reasoning that has gone into developing equations of motion. Try to remember your own science education in junior and senior high school and suggest how you would ensure that provision is made for adequate and appropriate evidence.

a. The balancing of chemical equations (grade nine).

b. Computing the current, voltage, and resistance in simple electric circuits (grade eight).

c. Determining the specific heat of a metal using a calorimeter (grade nine).

d. Calculating the velocity of a falling object (grade eleven).

e. Explaining osmosis on the basis of diffusion (grade nine).

f. Calculating the density of an irregular object (grade nine).

When we teach science we seem to emphasize the finished product of "scientific fact" and mathematical formulation in the teaching of physical science. Students, in turn, are often trapped by the efficiency of memorizing the "scientific fact" and the ease with which they can apply the "formulas" in solving exercise problems. The correct solution of the exercise problems then provides evidence for the teacher of the success of his/her teaching and it gives the student a sense of confirmation of mastery and understanding of the material.

This discrepancy between the *logic* of the textbook and the appropriate *evidence* to support it is apparent in the study of the physical sciences, especially in elementary physics. As former science students we remember in particular solving countless problems by using "formulas" based on laws, principles and definitions, and performing experiments to "prove" these laws. Newton's second law, for example, has been "proved" by students over the years, whether it involved the use of *Atwood's Machine*, *Fletcher's Trolley,* or the use of the *electronic air table.* Newton's first law, the textbook may have told us, is just a special case of the second law. But does that follow deductively? Can we perform experiments to "prove" the first law? Did Newton base his laws on experiments? If so, what experiments did he perform? On what assumptions are these laws based? Did he use inductive reasoning in arriving at these laws, as he insisted he did? If so, how is it that his laws are used as one would use a deductive system in geometry, as Whewell, among others, insisted could be done? Finally, why is it that if someone claims that Newton's laws were disproved on a special electronic air table no one will take that claim seriously?

Textbooks seldom deal with such questions. If they occasionally do, then the answers to them are given in footnotes, in quick historical references, but they are seldom seriously discussed. Science teachers in general, of course, are the product of textbook-centered teaching. It is therefore not surprising then that they, too, tend to bypass such questions. Science teachers generally fail to expose students to situations in which these questions are discussed. Such fundamental questions, however, must be discussed *before* going on to the mathematization and the working out of exercise problems.

Many students studying science therefore see little connection between their ideas about the world and what they learn in science textbooks (Aufshnaiter, 1989). We suspect at the outset that what lies at the heart of this problem is a sense of disconnectedness between the logic of the textbook and what "counts as good reasons for believing..." for the student.

## FOCUS QUESTIONS

These questions are to assist you in focusing on important points in the chapters. Your cooperative group should discuss them before each class. The class discussions will revolve around them.

1. Look up the word "evidence" in a dictionary. You will notice that in other complex notions such as energy, intelligence, creativity, it is difficult to provide a definition that does not contain the notion of "evidence", perhaps disguised as another word. For example, "energy" is defined in many science books as "the ability to do work". But "work" itself is later defined in terms of energy. How then do we escape this conundrum, or can we?

2. Discuss each of the five examples involving the idea of evidence.

    a. Show that to provide an adequate evidential basis from which to argue for a knowledge claim requires a reference to a background, ranging from <u>appeal to authority</u> to a thorough understanding of a <u>theoretical background</u>.

    b. Make up an example of your own (much like the ones above) in which you tell a story of how you defended a knowledge claim. Outline the background theory, make a knowledge claim and then set up an adequate evidential basis from which to argue.

3. Pick one of the "big" theories in science (Bohr's theory of the atom, the kinetic-molecular-theory of gases, Mendel's theory of genetics, the theory of evolution, Einstein's special theory of relativity) and outline the theory along the lines we have done with Newton' gravitational theory. You are not expected to give a complete report, a partial summation will be sufficient.

4. A student in a grade nine asks the question: "How do we know that atoms are made up of electrons, protons, and neutron?" How would you go about providing appropriate evidence, i.e. evidence that "makes sense" to the student?

5. It is puzzling that the word "evidence" occurs much more frequently in the biological and geological sciences than in the physical sciences. Why do you suppose this is so?

6. Following the examples given in the text, outline an argument for the following knowledge claims:

   a. The sun is round.

   b. The sun rises in the east and sets in the west.

   c. The sun is 150 000 km from the earth.

   d. There is Helium in the sun.

   e. Second-hand smoke causes lung cancer.

   f. Bacteria are about 1 micron long.

7. We perform experiments in class in order to provide <u>evidence</u> for theories, laws, "scientific facts", operational definitions, <u>etc</u>. Consider the following and indicate (describe) the kind of evidence you would try to provide for the student.

   a. A heavy body in free fall accelerates at a constant rate on (close to the surface of the earth).

   b. Archimedes' law of flotation.

   c. Organisms do not spontaneously generate from inorganic matter.

   d. The process of photosynthesis.

   e. F = ma, Newton's second law of motion.

   f. The density of air at STP is 1.29 $kg/m^3$.

   g. The temperature of liquid iron is 780 C.

h. The principle of conservation of energy.

8. It should be easy for you to recall a concept that you simply committed to memory, without being able to give an evidential argument that would sustain that concept. Take this concept or topic and try to connect it to the evidential plane.

9. Now attempt to place this concept on the three planes of activity. Devise a plan to teach it to a science class at an appropriate level.

10. The following activities in high school science are typical examples of topics that are often taught as rule-memorization (what we called algorithm-recitation). The activity that allows the student to solve successfully such problems often becomes just that, a purely puzzle-solving activity. When students solve these problems they are working on the logical plane. Working on the logical plane is fine but not if it is disconnected from the evidential plane in the experience of the student.

Thus students are able to balance equations, solve problems of free fall, etc., without a firm understanding of the concept of valence, or the reasoning that has gone into developing equations of motion. Try to remember your own science education in junior and senior high school and suggest how you would ensure that provision is made for adequate and appropriate evidence.

a. The balancing of chemical equations (grade nine).

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c. Determining the specific heat of a metal using a calorimeter (grade nine).

d. Calculating the velocity of a falling object (grade eleven).

e. Explaining osmosis on the basis of diffusion (grade nine).

f. Calculating the density of an irregular object (grade nine).

## Cooperative Learning Activity

**To the student**: The purpose of this activity is to bring about an exchange of ideas among students. You will be given between 10 and 15 minutes in class to meet in your cooperative group to discuss the issue and prepare to report back to the class on your group conclusions.

The Winnipeg Free Press reported the following front page news on June 20, 1991:

> Title: "Lines transmit cancer, study says". The article begins by explaining that electromagnetic fields are "bombarding" us daily from power lines and household appliances, have been linked to cancer in a "breakthrough" Canadian study. The article claims that researchers have found that laboratory mice are "three times more likely to develop tumours when they are exposed to electromagnetic fields". One of the researchers then stated that "With this experiment, we have some evidence that electromagnetic fields can affect cancer".
>
> The study found that one in three mice exposed to electromagnetic waves developed one or more tumours. On the other hand, only a little more than one in eight that were not exposed got tumours. For the study, 96 mice were given a tumor-promoting chemical. Half of the group was exposed to electromagnetic radiation, six hours a day, six hours a day, five days a week for 20 days. The other half was not exposed.
>
> Moreover, the mice were exposed to 1000 times the electromagnetic radiation that an ordinary person would receive while standing under a transmission wire.
>
> One representative of the electric power company pointed out that "this would be the first study involving mice that yielded a possible link". He maintained that "the overall evidence is weak". He then added: " If this were an agent that promotes cancer, it would be one of the great discoveries of the 20th century."

Evaluate this news item in terms of the soundness of the evidential argument and the background knowledge required to evaluate the evidence.

**Assignment #2:**

Use the **LEP model** of conceptual change and discuss how you would teach one of the following concepts or topics (assign and argue for an appropriate grade level):

a. Specific heat

b. The corpuscular theory of matter

c. Valence

d. Circulation of the blood

e. The solar system

f. Ohm's law

g. Bohr' theory of atomic structure

# Chapter 3

## How Science Advances

Kuhn's picture of science

Two examples of early confrontations in science

Confrontations in science

Progress in science

Problems with Kuhn's picture

Popper's ideas

Post-Kuhnian ideas

The notion that modern science is the result of an accumulation of knowledge resulting from new discoveries is still widespread, partly as a result of the way it is presented in textbooks. An interesting and relatively detailed account of the final overthrow of the theory of spontaneous generation appearing in a popular high school biology textbook is typical (Ref.) . The account describes in some detail how Louis Pasteur convinced the French Academy of Science that life does not generate spontaneously, but it leaves the impression that F. A. Pouchet, his opponent in the debate was bullheaded and unwilling to present his evidence to the Academy. It turned out that Pasteur's victory over Pouchet in the debate was more the result of serendipidy than better science. Pasteur's yeast and sugar medium was easier to sterilize than Pouchet's boiled hay infusion. As Pasteur's famously said: "Discovery favours the prepared mind".

### Thomas Kuhn: Revolutions in Science

Arguably the best description of how science advances was given by Thomas Kuhn. We will discuss his philosophy of science in more detail in chapter 10.

In his influential book, *The Structure of Scientific Revolutions*, Kuhn argues that the advance of science is a series of "revolutions", each ushering in a new phase of "normal science". He begins *The Structure of Scientific Revolutions*, with this now famous introductory sentence:

> History, if viewed as a repository for more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed (Kuhn, +1962**).**

Until Kuhn's seminal work historians and philosophers of science generally wrote about the history of science from the vantage point of the present in terms of a "logical and rational reconstruction". In other words, the main question was: "How should scientists then have acted if they had been as smart as we are today?" So the history of science was represented as a progression from "error" to "truth" as shown in modern scientific theories and concepts.

Early in his carrier, studying the history of science as a trained physicist, Kuhn asked the question: "How is it that Aristotle, who was so brilliant in other philosophical and scientific endeavours, could be so "wrong" in his physics?" Kuhn said (in a recent interview) that after a lecture he gave to arts students on Aristotle's physics the answer to that question came to him, while looking out his dormitory window:

> *Aristotle's views of such basic concepts as motion and matter were totally unlike Newton's. Aristotle used the word "motion", for example, to refer not just to change in position but to change in general-the reddening of the sun as well as its descent toward the horizon. Understood on its own terms, Aristotle's physics "wasn't just bad Newton, it was just different (John Horgan, 1991).*

All of us have had the experience of looking with disbelief at Aristotle's physics, the phlogiston theory of early chemistry, the theory of spontaneous generation or the caloric fluid theory of the late 18th century. We ask ourselves: "How could a scientist have believed these theories?" Behind this question, however, is an attitude of condescension that is generally referred to as the *Whig Interpretation* of the history of science. Of course, science textbooks generally reinforce this attitude.

Kuhn thought that in order to understand science in historical context we must look at history with new eyes. Indeed, he thinks we must become *Aristotelian*, *phlogiston theorists* or *caloric fluid theorists* if we hope to understand how scientists in these historical settings thought about the world.

We will use two examples that Kuhn used to illustrate his ideas. These are essentially straight-forward accounts of scientific inquiry in historical context that should present little difficulty to follow.

***The Phlogiston Theory: Example I***

Confrontations in science arise when two or more groups who *see* the world differently attempt to explain to each other the how and why of phenomena that are considered proper to their common domain of investigation. The evolution of the science of chemistry in the 18th century was one of the main examples Kuhn used to explicate his ideas. The phlogiston theory (from the Greek *phlogiston,* burnt) flourished in the 18th century. You may recall from your high school chemistry disparaging remarks being made about the naivete of this theory. How is it possible that such an "obviously wrong" idea became so entrenched in chemical thinking that a great intellectual effort had to be made to break away from it?" (Ronan, 1982). The fact is, however, that the phlogiston theory of combustion was very versatile and successful in explaining many fundamental discoveries. As Kuhn pointed out: "The much maligned phlogiston theory, for example, gave order to a large number of physical and chemical phenomena." (Kuhn,1962).

The phlogiston theory was based on Aristotle's idea that the world was made up of four elements-earth, fire, air and water. The theory was supposed to explain the nature of fire. Prehistoric man must have noticed that some substances burn while others do not. We know that the Greeks, who were the first to adopt a "rational" approach to understanding the world, did very little experimentation. The alchemists, on the other hand, who were guided by Greek ideas, experimented a great deal. They discovered that even metals would burn, leaving a calx (ash), that could not be burned. How can this be, they asked?

At the beginning of the 18th century the German physician and chemist George Stahl proposed the idea that phlogiston (Greek for "flammable"). He claimed that a metal was simply a compound of its *calx* and *phlogiston*. Burning was thought of as the release of phlogiston leaving behind a *calx*. Kuhn says about this versatile early chemical theory:

> *It explained why bodies burned-they were rich in phlogiston-and why metals had so many more properties in common than did their ores. The metals were all compounded from different elementary earths combined with phlogiston, and the latter, common to all metals, produced common properties. In addition, the phlogiston theory accounted for a number of reactions in which acids were formed by the combustion of substances like carbon and sulphur. Also, it explained the decrease of volume when combustion occurs in a confined volume of air-the phlogiston released by combustion "spoils" the elasticity of the air that absorbed it, just as fire "spoils" the elasticity of a steel spring.* (Kuhn, 1962)

The phlogiston theory explained why, when calx was heated with charcoal, a metal was produced; the charcoal was a flammable substance, rich in phlogiston while the calx (it does not burn) had no phlogiston. The phlogiston was transferred from the charcoal to the calx yielding a metal. The great chemists of the 18th century, Black, Cavendish, Priestley, and even Lavoisier were confirmed phlogistonists, at least at the beginning of their research activity. Their experimental activity was guided by a small number of elementary principles of which the phlogiston theory was one.

Kuhn describes the principles and theories that guided these 18th century chemists as a *paradigm*. The *Phlogiston Paradigm* both guided their scientific thinking and clearly established what was accepted as, what he calls *normal science*.

Soon, however, Black and Cavendish showed that it was no longer possible to think of air as one of the elements. They discovered other constituents of air, *inflammable air* (hydrogen) and "fixed air" (carbon dioxide). Later careful measurements, using newly developed analytical balances, showed that these gases were "heavier" than air. In addition, these gases had different chemical properties. By 1773 Lavoisier showed (using painstaking measurements with the new balances) that when water was boiled the *earth* residue was not due to water changing to earth, as the current paradigm required; the *earth* must have been in the glass pelican used. Finally, Priestley discovered what he called *dephlogisticated air*, a gas that had extraordinary properties. He remained faithful to the phlogiston theory of combustion to the end of his life in 1814. Lavoisier later renamed this gas ***oxygen*** which means *acid former*.

### *Lavoisier Rejects Phlogiston*

By the mid 1770's Lavoisier began to seriously question the phlogiston theory of combustion. He devised experiments that were guided by the idea that there are not four, but many elements that were responsible for making up compounds. For example, he found that when sulphur and phosphorus were burnt in air both gained weight (mass) in burning. Moreover, on heating the calx of lead (lead oxide) with charcoal a gas (we now call the gas $CO_2$) was liberated. It should be clear to you why this was a clear contradiction to the phlogiston theory.

In his final memoir (1783), summing up his arguments against the phlogiston theory Lavoisier wrote:

> *... to show that Stahl's phlogiston is imaginary and its existence in the metals, sulphur, phosphorus and all combustible bodies is a baseless supposition and that all the facts of combustion and calcination are explained in a much simpler and easier way without it.* (Scott, 1988)

Lavoisier's oxygen theory was simpler; it provided an explanation for all that the phlogiston theory could and also accounted for the mass gain during combustion. Moreover, the new chemical theory made the bold assertion that the "element" water was really a compound of oxygen and hydrogen. What was still needed was the imaginative atomic theory of Dalton that allowed chemists to make a clear distinction between mixtures and compounds.

A revolution in the way chemists explained chemical phenomena was under way. According to Kuhn, during a scientific revolution, like the chemical revolution that overthrew the phlogiston theory, a *gestalt*-switch takes place. This is a transformation of vision; where Lavoisier "saw" oxygen, Priestley saw dephlogisticated air and still others saw nothing at all. Moreover, Lavoisier "saw" a compound ore where Priestley and others continued "seeing" an elementary earth. As Kuhn puts it: "after discovering oxygen Lavoisier worked in a different world" (Kuhn, 1962).

***Early Electric Theories: Example II***

In the science of electricity in the 18th century there were "almost as many views about the nature of electricity as there were important experimenters ....". It is interesting that several "wrong" guiding principles led the "electricians" of the eighteenth century onto the right path. They developed a consensus on an underlying mechanism for explaining their experimental findings that provided them with direction for new experiments as well.

For example, the discovery of the Leyden jar, "a device which probably never would have been discovered by a man exploring nature casually or at random", was based on the notion that electricity was a kind of fluid, a fluid model of electric phenomena. But it was precisely the effort to explain the phenomenon of the Leyden jar that lead Franklin to the *electric charge* concept that we are familiar with today. Kuhn emphasizes this new way of "seeing":

*... after the assimilation of Franklin's paradigm, the electrician looking at a Leyden jar saw something different from what he had seen before. The device had become a condenser, for which neither the jar shape nor the glass was required. Instead, the two conducting coatings-one of which had been no part of the original device-emerged to prominence*.

This way of "seeing" the Leyden jar ultimately led to the concept of the modern capacitor that became the prototype of all our electronic devices of today, including such high-tech devices as the microchip. The study of electrical action-at-a-distance could now be a legitimate study and the phenomenon we now call *charging by induction* could be explained as one of its effects. We can say that, like Galileo looking at a swinging body and seeing a pendulum rather than Aristotelian constrained motion lived in a different world from the Aristotelian, so the new "electrician" of the late eighteenth century, after accepting the condenser model, worked in a different world from the *fluid theorists*.***Comments For The Two Examples***

The effect of thinking in terms of many elements making up all the compounds, reinterpreting combustion as the uniting of oxygen with another substance, and routinely depending on accurate and precise measurements of the weights of reactants and products, ushered in the new chemistry.

Similarly the effect of hitting upon a simple plausible mechanism underlying all diverse electrical phenomena had revolutionary consequences. First it gave direction to research; the discovery of ***Coulomb's law***, for example, is inconceivable without the guiding notion of point charges affecting each other at a distance. Secondly, it transformed the group "previously interested merely in the study of nature into a profession or, at least, a discipline."

The members of the group of a newly-formed science, like those of the new chemistry around 1790, and like the members of the new science of electricity around 1800, stopped arguing endlessly over presuppositions, discontinued working on "puzzles" unconnected with the domain defined by the group's new way of "seeing", stopped dealing with mavericks and cranks, and began to communicate by way of their own journals.

Once the warring groups (in our examples the phlogiston theorists and the "new chemists", and the "electricians" with their various modes of explaining electrical phenomena) agreed on presuppositions and a set of theories to guide their research, they were on the road that lead to the assimilation of a time-tested and group-licensed way of seeing. The members of the newly-formed scientific discipline now spent most of their efforts in deciding what the genuine problems of their discipline were and became oriented to what Kuhn calls *puzzle-solving*. This state of affairs requires for the members to take the foundations of their field for granted.

Finally, it is desirable that the new scientific specialty become reconcilable with the dominant scientific view of the age. In the case of the new science of electricity, roughly around 1800, Coulomb's law, for example, had to be successfully incorporated into Newtonian physics. Initially this presented difficulties because of the presence of repulsive forces, not accounted for in Newton's *Principia*. Only after the recognition of a new kind of force in nature, that acted on charged particles according to Coulomb's law (like Newton's law of gravity this turned out to be an inverse square force) could the new science of electricity be incorporated in the larger paradigm of Newtonian physics.

**The Notion of Paradigm**

Based on our two examples we can summarize and elaborate a little on the idea of ***paradigm***. Kuhn generally seems to identify the notion of *paradigm* with what it is that underlies and gives coherence to a research tradition. He argues that the practising scientists in a given *paradigm* are active in what he calls *normal science.* The *normal scientist* learns to identify problems and techniques associated with a research tradition. Scientists recognize these because of a *resemblance* to already successful achievements within the *corpus* of science, and not because they are the product of a *method*, or a set of rules. Scientists, in fact, become members of a research tradition as well as "believers" in a paradigm. This is achieved by virtue of their training and their science education, the literature they read, and what they recognize as standard models and solutions of their craft.

The activity that Kuhn calls *normal science*, however, can go on only so long as the solutions to the problems posed by the paradigm are accepted by the research group. When the solutions to some important problems are challenged then debates begin to take place *over legitimate methods, problems, and standards of solution.* Attempts to identify and then question the foundations and the *presuppositions* of a tradition usually signal the beginning of a crisis. Problems begin to pile up that stubbornly refuse solution by methods sanctioned within the paradigm.

## Progress in Science

According to Kuhn science can progress on two levels; during the long period of *normal science*, and also during the shorter period of a successful *revolutionary science* that ushers in a new research tradition. On the first level scientists who are trained in a common intellectual tradition attempt to solve the problems that the tradition generates, which then are expected to be soluble in its terms. On the second level a mature science, like physics, progresses with the succession of traditions, (Aristotelian, Galilean, Newtonian, Einsteinian), each with its own methods of research . Each of these traditions guides a community of scientists for a period of time, and each in the end is abandoned.

The need to abandon a tradition in favour of a new one is signalled by the accumulation of long-standing problems. These are problems that prove unyielding to the research methods of the old tradition, however cleverly applied by the most skilful "puzzle solvers". With the piling up of such problems a crisis period is reached when scientists actively look for alternative ways of solving them. Eventually one of these, based on a new set of metaphysical assumptions and new methods of solutions, wins the allegiance of most scientists. A new disciplinary matrix develops that is able to solve these problems. What counted as scientific knowledge in the old tradition is reconceived, re-evaluated, and sometimes discarded. Textbooks are rewritten, science education is changed, and the scientist sees the world differently.

***Problems with Kuhn's Picture of Science***

There are problems, however, with Kuhn's picture of how science progresses. Kuhn argues that normal science, alternating with periodical revolutions is the only way a mature science like physics grows. Yet science must grow in different ways. For example, one can understand Einstein's special theory of relativity as an attempt to reconcile Newtonian mechanics with Maxwell's electromagnetic theory, and his general relativity theory as an attempt to unify his special theory and Newton's theory of gravity. Einstein did not develop these theories in response to an accumulation of commonly perceived problems or anomalies. Moreover, a research tradition may find itself in a state of near crisis, not because of the piling up of difficult problems, but because of problems at the foundation of the science. At the moment both general relativity and quantum mechanics are under attack because of theoretical difficulties (Dicke, Bohm).

Finally, Kuhn does not explain why sometimes anomalies precipitate a revolution in science and other times they do not. For example, the precession of the perihelion of Mercury was an anomaly known in the middle of the nineteenth century, but the discovery merely prompted astronomers to seek solutions within Newtonian physics.

## Rationality in Science

Kuhn defends the rationality of *normal science* on two grounds. First, the scientist who works within a disciplinary matrix can do so very efficiently, in the sense that the class of problems and the techniques for their solutions are already available. Secondly, every research tradition, or disciplinary matrix is expected to be eventually superseded by one that can explain all the standard problems of the present tradition and solve the outstanding anomalies of the old tradition. Moreover, a necessary (but not sufficient) condition of rationality in science must be collective agreement, and that is achieved if Kuhn's picture of normal science is correct.

Kuhn admits that the rationality of revolutionary science, however, cannot be so easily defended. According to Kuhn, when a theory like Einstein's general relativity theory replaces Newtonian gravitational theory, the two theories become *incommensurable.* This is so because, as we have already noted, such fundamental notions (or terms) as "mass" and "energy" take on completely new meanings in the new tradition. Moreover, since scientists are looking at the world through different exemplars, they "see" different scientific facts.

It is clear that according to Kuhn's picture of science there is no logical way one can discover a new theory, nor show that one theory is superior to another. Members of the "old tradition" are therefore either *persuaded* or c*onverted* to accept a new way of seeing. Persuasion, however, may or may not be followed by conversion. Persuasion, according to Kuhn, is connected with one's resignation to the obvious superiority of one theory in solving outstanding problems over the other's. For example, Einstein's relativity theories can solve all the problems Newton's can and is able to "explain" such anomalous behaviour as the precession of the perihelion of Mercury.

Conversion, on the other hand, is connected with whether or not one can make a *gestalt switch* when embracing the new theory. Scientists in their middle years, for example, who had received their scientific education based on Newtonian physics only, were able to intellectually accept quantum mechanics and relativity, but were never "converted" to it. Kuhn likens such a person to the translator who translating a theory or world view into his own language is unable to make it his own. We must remember, however, that Kuhn does not say that absence of logic can be equated with absence of reason.

Both normal science and revolutionary science then must be seen as irrational for the following reasons. There is no need for the working scientist to examine the foundations of his craft critically, for he must take them for granted. This constraint limits his range of inquiry and the rate of growth of his tradition. Kuhn claims, however, that without the concentration that only the security of the context of normal science can give, progress would be slow, if not impossible. Moreover, the search for a new theory is supposed to take place only when the security of normal science is disturbed by the piling up of unsolved problems.

Criteria for acceptance of a theory should go beyond its ability to solve immediate problems. Such criteria as problem-solving ability in general, simplicity, and aesthetic components are also criteria to be used when accepting a theory. We have also argued that such criteria must be imbedded in a presuppositional structure of a science. If this picture of science is correct, then it is rational to accept metaphysical presuppositions, such as *the world is intelligible* , precisely because these are empirically not testable. The philosopher of science Nicholas Maxwell, for example, argues that unless we accept as a metaphysical presupposition that the world is rational, *science cannot get off the ground,* and is doomed to remain an irrational enterprise.

> *...the aim of seeking intelligibility in the universe is rational, not because we have good reasons for supposing that this aim can be realized (in that intelligibility really does exist") but rather because, as far as science is concerned, we place such supreme value on intelligibility that we are willing, quite rationally, to hunt for it even though we cannot know what we seek "really exists".*

## Modern Confrontations

We are inclined to think of modern science as having resolved most issues. Quite the contrary is true, science in the 20th century was fraught with confrontations, some completely or partly resolved, others still raging. The following are some examples of more recent science confrontations.

a. Gamow's big bang theory vs Hoyle's steady-state-theory in cosmology

b. Cold Fusion in physics vs chemistry

c. In geology, plate tectonics vs an immovable earth crust

c. In biology, punctuated vs gradual evolution

d. In human evolution, displacement of pre-Homo sapiens by outward migration from Africa vs in situ evolution

d. Planck's quantum theory vs classical electrodynamic theory

f. Einstein's special theory of relativity vs Newtonian physics

g. Schroedinger's wave vs Heisenberg's matrix interpretation of quantum mechanics

k. Action-at-a-distance versus instantaneous action in quantum mechanics.

Some so-called scientific confrontations are, in fact, only pseudo-scientific confrontations. The creation vs evolution controversy would clearly be considered a pseudo-confrontation in the context of Kuhnian science. Protestations to the contrary, creationism rests on biblical evidence while the propositions of evolutionary theory are justified by scientific observation of the natural world. From a Kuhnian point of view, astrology, tarot card reading, and other attempts to foretell the future through mystical means would be considered irrational belief systems.

## *Theories, Hypotheses, and Laws*

Theories are explanations that link what might otherwise be several isolated phenomena together. For example, phenomena such as temperature, the gas laws and evaporation are all explained by kinetic-molecular theory of heat. Although theories are sometimes referred to as models, philosophers of science usually restrict the term "model" to more limited explanations such as "the Bohr Atom".

One often hears the comment, that's only a theory, it hasn't been proven yet. In science, theories are never proven, but as we will see later they may be disproved. Consider the following example from physics. In 1911, the prevailing theory of the structure of the atom first proposed by J. J. Thomson was that it was like a ball of positively charged cotton with electrons embedded in it. Ernest Rutherford reasoned that if this were the case, the positive charge on a thin layer of such particles should be evenly distributed. Accordingly, if a heavy projectile bearing a positive charge were to strike the surface of a thin layer of atoms with sufficient force, it would pass through without being deflected. If on the other hand, the charge on the thin layer were concentrated in globs, positively charged projectiles striking or passing near the globs of positive charge would bounce back, or be deflected away from them while those projectiles that missed the globs completely would pass through undeflected.

For an experiment to test Thomson's theory, Rutherford chose as his thin layer of atoms, a very thin gold leaf; for his projectiles, alpha particles (helium nuclei with a charge of +2 and a mass of +4) produced by the radioactive decay of polonium.  To create a thin beam of alpha particles, a sheet of lead with a small hole in it in was placed in front of the polonium and the beam aimed at the gold foil.

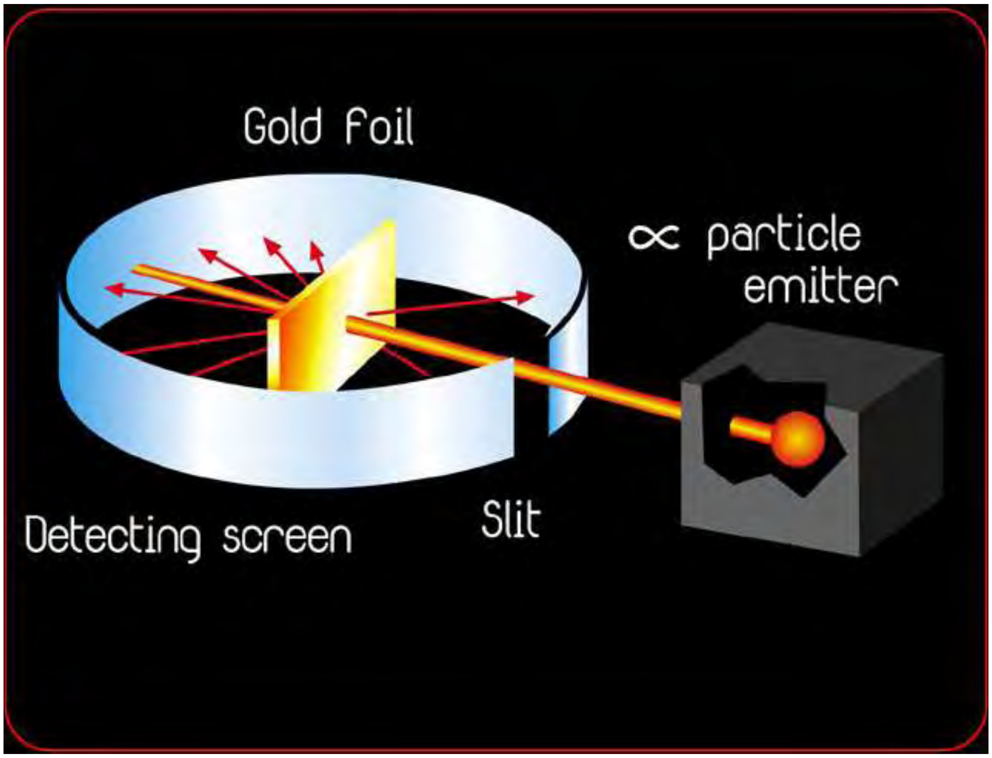


**Figure 1** Rutherford's apparatus for observing the effect of a thin layer of molecules on alpha particles

Since the effect of alpha particles are too small to be seen with the unaided eye, a detector was required. Zinc sulphide which gives off a flash of light when struck by an alpha particle, was placed behind the gold foil.

To his surprise, Rutherford found, contrary to what was predicted by J. J. Thomson's atomic model, that while most alpha particles passed through the foil without being deflected, some particles were deflected. From this observation, Rutherford inferred that the positive charge could not be evenly distributed but must be concentrated in small globs with large spaces between the them. Only those alpha particles that struck or passed near the globs of positive charge were deflected while the others were not. He called the positive charged globs atomic nuclei, paving the way for the modern theory of atomic structure.

Besides serving as explanatory schemes, theories also guide future research. If Rutherford had experimented randomly he probably would never have thought to perform his experiment. Because he had Thomson's model of the atom, he was able to use a deductive process similar to an if-then statement. If Thomson's model is true and I do A, then I should observe B. Such an if-then statement can be called a hypothesis. Rutherford was testing the hypothesis that alpha particles would not be scattered when passing through thin gold foil.The hypothesis proved to be false and Thomson's theory of the structure of the atom was discarded requiring the construction of a new theory (model) that accounted for the scattering of alpha particles.

If a theory can be considered provisionally true, that is if it seems to be in accord with nature, any hypothesis derived from it should also be acceptable. If a theory is false, then a hypothesis derived from it may be true or it may be false. Accordingly, a theory can never be proven true, only proven false. Theories are abstract explanations of reality that can never be proved true but if hypotheses can be generated from it that turn out to be false, then the theory must be false

## Focus Questions

These questions are to assist you in focusing on important points in the chapters. Your cooperative group should discuss them before each class. The class discussions will revolve around them.

1. Since the publication of *The Structure of Scientific Revolutions*, expressions such as paradigm change and new paradigm have become common parlance. Perhaps that is an overstatement; one hears them from time to time, particularly among social critics. Find some examples of the use of

*paradigm* in a context other than Kuhnian, and compare and contrast its meaning with the way Kuhn used it.

2. Recall one of your university science textbooks. Did it present theories and principles in a tentative way or were they presented pretty much as facts? Should it have?

   Examine a school science textbook. How does it present science? Should it present science differently, and if so, in what way?

   You might also look up *paradigm* in the dictionary to get a sense of its traditional meaning.

3. Consider an astrophysicist photographing objects in the night sky in the year 1993. Now consider a shepherd in the middle east in the year 2500 B.P. tending a flock of sheep on a starry summer evening. The shepherd in a reflective mood, is contemplating the points of light above him.

   Would both be experiencing the same *reality*?

   How might their realities differ?

   Which reality is "truer"?

   How do you know that?

4. What is wrong with the following statement? Once Newton demonstrated that gravity existed, his theory of gravitation became a scientific principle.

5. We introduce Thomas Kuhn by quoting the first sentence of his famous book. Explain this quote in your own words.

6. What example was given in your text that seemed to contradict Kuhn's model of how science progresses? Think of some other examples in science that do not conform to Kuhn; some examples that support Kuhn.

7. According to Kuhn, what do modern "normal" scientists do?

8. Briefly elaborate on Kuhn's concept of *incommensurability*. Give examples in physics, chemistry, or biology of incommensurability.

9. The authors assert that the controversy between the biblical creationists and evolutionary biologists is a *pseudo-confrontation*? Do you agree or disagree? Why?

   Suggest some other *pseudo-confrontation* that are not listed in this chapter.

**Assignment: A Cooperative Learning Activity**

To the student: The purpose of this activity is to bring about an exchange of ideas among students. You will be given between 10 and 15 minutes in class to meet in your cooperative group to discuss the issue and prepare to report back to the class on your group conclusions.

A controversy is raging between physical anthropologists and geneticists and molecular biologists regarding human evolution.

Physical anthropologists propose that modern *Homo sapiens* evolved simultaneously worldwide from a pre-existing species, most likely *Homo erectus*. Their proposition is supported by the fossil record in which *Homo erectus* fossils are widely distributed across the world and are not overlapped in time by fossils of *Homo sapiens*.

Geneticists and molecular biologists propose that *Homo sapiens* evolved in Africa after *Home erectus* had spread across the world. *Homo sapiens* then fanned out from Africa, eventually displacing *Homo erectus*. The evidence for their proposition comes from the study of mitochondrial DNA. When fertilization occurs, the egg receives only DNA from the nucleus of the sperm. Mitochondria, cell structures that also contain DNA, lie outside the nucleus. Hence, all mitochondrial DNA is passed from mother to mother without mixing with the father's DNA. By sequencing and comparing mitochondrial DNA geneticists can trace the genetic heritage of individuals.

When human geneticists compared mitochondrial DNA of various groups of humans, they proposed that all *Homo sapiens* (modern humans) are derived from a very small group, some going so far as to say from one mother, in Africa.

1. Do both of the propositions described above meet the requirements for being scientific theories? Justify your answer.

2. Identify each of the following in the two propositions: assumption, hypothesis, theory, scientific principle, observation, operational definition?

3. Could both be true?

4. What evidence would be required to prove that one them is false?

5. What evidence would be required to prove that one them is true?

# Chapter 4

## The Nature of Science and Science Education

Students' ideas about science

The central question of scientific inquiry

Reasoning in science: inductive or deductive?

Examples of scientific reasoning

An attempt to solve the puzzle of induction

The role of explanation in science

Our present understanding of the nature of science

**Students' ideas about science**

As a science teacher your views and understanding of the nature of science will determine what you teach (content), how you teach it (paedagogy) and what you emphasize (personal knowledge, values and attitudes). For example, a science teacher may believe that there is a specifiable "scientific method" that scientists have adopted and use in their daily work. Further, he/she may believe that this method can be characterized and described, easily taught, and that its proper use will guarantee scientific results. It is a plausible assumption then that the teacher will teach science in a way that will emphasize what we will later call an 'empiricist-inductivist' view of science. This view of science seems very commonly held and is based on the belief that science starts with observation and data gathering, and the establishing of 'scientific fact', all supposedly objectively taken. This picture of science emphasizes the priority of observation, which then are supposed to provide the base for inductively arrived at generalization and laws. Generalizations and laws constitute the finished product of organized science and are enshrined in our textbooks for the students' consumption. In other words, the science teacher will probably present the finished products of organized science for the students to memorize. Students will occasionally do experiments, to be sure, but they are of the type that 'verifies' the findings of science.

Students' ideas about science and what scientists do are shaped largely by their school experiences. Of course, they are also effected by social and cultural influences, especially by what they see in movies and on TV. Science education researchers (N. Burbules and Marcia Linn), however, argue that, despite the influences that are outside the school's control, what interferes mostly with students' acquisition of a good understanding of the nature of science grows out of the way science is usually taught. They refer to the instruction that is based on "learning facts and technical vocabulary", and to approaches that "frequently assume a static view of scientific knowledge and present a single 'method' that purpotedly characterizes all scientific investigations" (page 228). The researchers argue that an approach that is based on the picture of science that is static and that assumes the existence of a single method leads to the following. First, students will perceive the learning of science as the memorization of facts and formulas. Secondly, students will largely fail to see a connection between the science they learn in school and the science problems they encounter in their every day life. Indeed, students seem to distinguish clearly between 'school science' and 'every day science'. Thirdly, students gain an inaccurate understanding of how scientists work because science learning in school is almost entirely individual and non-social.

Other researchers agree with the above brief assessment of science teaching (Hodson, 1989, p. 21). They, too, think that children's general attitudes toward science, what they understand about the nature of science and what scientists do comes mainly from two sources. These are their school experiences and the "existing public image as portrayed by informal learning channels" (Hodson, p. 21). It seems that attitudes are formed very early and what determines these are mainly teaching style and the teacher's own image of science. The science educatator Herbert Smith, in a special study reporting on pre-college science education for NSF, claims that the effect of this is that "what a given teacher believes, knows and does as well as he/she doesn't believe, know, and do, represent what science education will be for a given child" (cited in Abimbola, 1983, School science and Maths. V 83(3)).

Science educators Fenstermacher and Soltis (see Abell, 1989) go even further and argue that the teacher is altimately responsible for portraying the nature of knowledge in *any subject area* (see Abell, p. 2.).

Outside influences, such as movies and TV programs largely reinforce the image of science presented in schools. We will be discussing the influence of the media on the image of science in general later on in some detail. There are reassuring signs, however, that the image of science as portrayed by the media is changing. It seems to be shifting from static picture of science based on a clearly specifiable method to a dynamic one, based on the complex interaction between human imagination and theory construction. This picture of science recognizes that observations depend on a theoretical viewpoint, that theories are fallible and are human constructs within a research tradition. Such TV programs as NOVA, movies like "The Race for the Double Helix" and books like Stephen Hawking's A Brief History of Time promote a picture of science that falsifies the conventional one described by the following exerpt:

The scientist of the school science is revealed as a depersonalized and idealized seaker after truth, painstakingly pushing back the curtains the curtains which obscure objective reality, and abstracting order from the flux, an order which is directly revealable to him through a distinctive 'scientific method'. (Quoted in Abimbola, p. 189).

Is the teaching of science in the classrooms also shifting away from a static picture of science to a dynamic one? Before answering that question we will discuss what the philosophy of science has to say about the nature of science science and scientific inquiry.

## Central Problems of Scientific Inquiry

Philosophers of science deal with the nature of scientific inquiry. The central problems they consider are the problem of induction and the problem of explanation. The first deals with the question of how we can go from a limited set of data to sweeping generalizations about the objects and events of the natural world, and the second relates to the question of why phenomena take the form they do. Let us look at these problems in an effort to show how they have generated the main questions that major schools of thought of the philosophy of science are still attempting to answer.

### Reasoning in Science: inductive or deductive?

The notion of deductive reasoning arose among the Ionians (Thales. c. 600 B.C.) and was later developed by the Greeks, notably by Aristotle and Euclid. Here is a simple example of deductive reasoning from mathematics. In Euclidean geometry we argue:

**Premise 1.** The internal angles of all triangles are equal to $180^o$, exactly.

**Premise 2.** This is a triangle that has two angles that add up to $160^o$.

**Conclusion:** Therefore, the third angle has a measure of $20^o$

Again, the conclusion is guaranteed to be correct. How do we test for the validity or "logical truth" of this theorem? Do we go ahead and measure the internal angles of as many triangles as possible and then generalize? Of course not. In Euclidean geometry, we establish "self-evident" axioms, such as the axiom that "parallel lines never meet" and establish certain rules of inference. We then deduce theorems (like the one used above) and argue for specific cases. But suppose we say:

**Premise 1.** We have tested many metals for electric conductivity. They were all good conductors.

**Premise 2.** This unknown object is a metal.

**Conclusion:** Therefore, this unknown object is a good conductor.

Premise 1, usually referred to as the major premise, is a generalization arrived at by testing many but not all metals. Because the major premise is uncertain, we cannot be absolutely sure that the untested metals are conductors. Therefore, the conclusion cannot be guaranteed to be correct.

If it turns out that the unknown object is, in fact, a good conductor, we can describe the conclusion as an "empirical truth". The main distinction between logical validity and empirical truth is that *empirical truth* relates uniquely to our theories about the world. Logical validity which may be called *logical truth* is true in all possible worlds.

**Large Scale Theories**

In scientific inquiry we also try to establish large-scale theories that allow us to make predictions by a deductive method of reasoning, not unlike the reasoning employed in geometric arguments. Let us look at how we test for the "empirical truth" of one of the great generalizations in science, namely

Einstein's general relativity theory (GRT). The theory made certain "daring" predictions such as the precise amount of bending of star light in the gravitational field of the sun.

Very few people understand the reasoning behind this difficult theory. However, even if we do not understand the conceptual network of the theory we can still understand the deductive nature of the arguments. Einstein first established an axiomatic system that included such axioms as *the speed of light is constant relative to all observers*. From this theory then it followed, by mathematical and logical arguments, that light (from the stars) must bend a certain amount in the gravitational field of the sun. Measurements were then taken in North Africa during the 1919 solar eclipse by the great English physicist Eddington to confirm this prediction. Indeed, it was found that star light bent in the vicinity of the sun exactly as Einstein predicted. We should mention at this point that Newton's gravitational theory also predicts a bending of light in the gravitational field of the sun, but only at about half the value that Einstein's GTR predicts.

How did Einstein arrive at this axiomatic system from which he could make such testable predictions by deductive reasoning? Einstein himself acknowledged the role of intuition and imagination in the construction of large scale theories in contrast to Pearson's specifiable scientific method. Similarly Aristotle over 2000 years earlier believed that scientific principles were discovered through the power of the power of intuition and imagination. However, both believed that once the theoretical background (laws, principles, definitions) was established we could reason deductively to find facts. See in Figure 2 on the next page how he explained such theories are constructed.

**Theories and Their Consequences**

The point we are trying to make is this: theories in science (especially the "big theories" like Newton's gravitational theory and the kinetic molecular theory of gases) have deductive consequences that follow as surely as the fact that the third angle of a given triangle must be 20. If a deductive consequence of a physical theory is deemed significant (say, that the period of the moon's rotation around the earth is 28 days) and can be measured, and is later found to agree with the predicted value, then we have a good theory. Does this mean that the theory is "true"? No. It only means that as far as this significant prediction is concerned it is a good theory. There could be other theories (also of a deductive nature) that could make the same testable prediction **and**, in addition, make other ones that the first theory could not

Let us now restate the argument for the "empirical truth" of the GTR. From the physical point of view we have to place the argument this way:

**P1** If light bends S seconds of arc as it passes by the sun then Einstein's theory of general relativity **must be true**.

**E** It is the case that when light passes the sun it bends S seconds of arc.

**C** Therefore, Einstein's theory of general relativity is true

Arguing this way, however, our conclusion may not be true. We can represent this argument as a syllogism:

| | | | | |
|---|---|---|---|---|
| **P1** | T | if | E | If T is true, we see E |
| **P2** | E | | | We see E |
| C | then | T | | Therefore, T is true. |

Premises **P1** and **P2** may be true but what about the conclusion C? We are not justified in drawing the conclusion that T is true. To do so would be to commit what is commonly known as "the fallacy of affirming the consequent". Can you make up an argument similar to this one that fits this schema?

For example, the Phlogiston Theory of the 18th century predicted that burning would release phlogiston which was supposed to have negative mass. Indeed, combustibles such as magnesium and aluminium do have greater mass after burning. Therefore, as far as the alchemists were concerned, the theory was confirmed. Of course, even a well-confirmed theory, according to this reasoning (often called the "the inductionist fallacy), may still be false.

In general then, confirmation in science, whether the grand GTR or the humblest hypothesis, means drawing logical implications from some hypothesis (H) or theory (T) to some empirical-experimental prediction (E). Thus, if T or H is true then E will be observed. If E is indeed observed, scientists might claim that T is confirmed or verified. However, we have just shown that this claim cannot be made. We can never truly "verify" any theory, not even the most successful ones.

Scientists then try to construct theories from which it is possible to argue in a deductive fashion to experimentally testable predictions. The experimental testing, while it may **confirm** a theory for that particular significant prediction, is never "verified".

Before theories are developed, scientists often have to reason inductively, that is, make a generalization on the basis of a limited number of examples. Here are some examples of inductive reasoning:

1. We have tested many different kinds of metals: they all expanded when heated. Therefore, we conclude inductively that all metals expand when heated.

2. The modern periodic table of the elements was first proposed by the Russian chemist Dmitri Mendeleev. Mendeleev arranged the 70 or so elements known at the time into columns of increasing mass. He then matched elements in each columns with elements in other columns that had similar chemical and physical properties. The result was a set of columns and rows that comprised the first periodic table. Since he was looking for patterns in an otherwise chaotic set of data, the logical processes involved can be said to be inductive.

   Later, Henry Mosely discovered atomic numbers and rearranged the elements according to atomic number. It was deduced from blanks in the periodic table that undiscovered elements must exist. This led chemists to search for new elements that would fill in the gaps in the periodic table. One such element is helium with an atomic mass between hydrogen and lithium. Helium was actually "discovered" in the sun by spectroscopy before it was found on earth.

3. The study of biology offers some of the more interesting examples of the use of inductive reasoning in science. The generalization that nothing lives forever is an excellent example of inductive

reasoning in biology. Over the centuries, people noted that animals seemed to have a finite life span. Even poets subscribed to that generalization as evidenced by the 19th Century poet Swineburn's Garden of Proserpine:

*We thank with brief thanksgiving whatever gods may be;*

*That no life lives for ever, that dead men rise up never;*

*That even the weariest river winds somewhere safe to the sea.*

Observers have also noted that after many cell-divisions, single-celled organisms must undergo some sort of cell fusion. If for some reason, this does not occur, the cell population dies out. In more recent years, a biologist named Leonard Hayflick discovered that after 50 to 60 divisions (yielding some $10^{18}$ cells from one cell) animal cell cultures become senescent. From observations such as these, biologists have concluded that multicellular organisms, particularly animals are mortal, and have a finite life span.

The generalization that multicellular animals are mortal resulted from observations of a large number of cases. As of now, there is no established theory, however, from which such a prediction would be made. An immortal space traveller visiting Earth for the first time, who was metabolically similar to us might be surprised to find that animal life on Earth was mortal.

All of these examples are connected with the central problem of induction. The question of induction in science can now be stated:

> "What sort of reasoning is it that allows us to make generalizations that are more comprehensive than the facts on which they are based?" The word *generalization* can be seen as *theory*, like Newton's theory of gravitation or Darwin's theory of evolution.) As Gerald Holton, a leading historian of science has put it: "At the least it has become clearer in our day that the pursuit in science is itself not a science" (Holton, 1980, p. 386).

Over 200 years ago the English philosopher David Hume argued that induction cannot be justified. He argued that only deductive or demonstrative arguments, like those in geometry, lead to certain conclusions from self-evident premises. Inductive or generalizing arguments proceed neither from self-evident premises nor do they lead to certain conclusions. So he concluded that scientific knowledge based on induction is suspect. In connection with the problem of induction, the 20th century mathematician and philosopher, Alfred North Whitehead was led to remark that "science went right ahead, not knowing that Hume had refuted it".

It seems that what scientists do is generalize *inductively* and then argue *deductively* from these generalizations to specific instances with confidence (See figure 2). What is puzzling here is that:

a. often a generalization can be arrived at from a very few instances, and

b. further multiplication of instances does not seem to strengthen the commitment to the generalization.

## The Problem of Explanation in Science

The problem of induction deals with the question of how we can go from a limited set of data to generalizations that can go beyond those data. Explanation in science, on the other hand, is connected with the question of "why do phenomena take the form they do?". Explanation in science is connected with the construction of a theoretical framework that offers a good description of phenomena and allows us to draw deductive consequences. For example, Newton was able to construct a theoretical framework that contained law-statements to account for and describe the elliptical motion of planets. However, these laws not only enable astronomers to give an accurate account of events but also allow us to make astonishingly precise predictions. Therefore explanation and prediction seem to be intimately connected. Philosophers of science have developed various theories characterizing the nature of scientific explanation and how explanation is related to prediction.

Scientific theories, however, can evolve from "from mere predicting devices" to genuine explanatory theories. Babylonians were able to discover arithmetic algorithms to predict heavenly motions. However, they payed no attention to "explaining" celestial phenomena. You may recall that the Ptolemaic model of the solar system preceded Copernicus. Ptolemy's model was an excellent predictor even though it assumed that the planets as well as the sun revolved around the earth. The astronomy of the early Ionians, on the other hand, was based on speculation, models and theory, but was unable to make predictions. Harre argues that the ultimate objective of scientific inquiry ought to be theories that have reliable predictive value and are based on understanding the underlying mechanism (Harre, 1971).

Moreover, it seems clear then that we simply do not have explanation/prediction symmetry in science, except in rare cases. Let us look at a number of cases that would be considered spanning the explanation/prediction spectrum.

1. It is possible to make very precise (reliable) predictions from the symptoms associated with diseases. However, it would be absurd to say that the symptoms explained the subsequent syndrome.

2. We can predict that a heavy object near the surface of the earth will take so many seconds to fall a given distance. However, we cannot explain why the acceleration is what it is, because we do not have an understanding of the nature of gravity. Our understanding, based on Newtonian physics, is really only a description, not an explanation.

3. When we heat a metal we predict that it will expand. However, to explain why this takes place would require a good understanding of atomic theory and thermodynamics.

4. In the theory of organic evolution specific predictions about life forms are difficult to make. However, the theory gives a good explanation of why, under certain conditions the species that are encountered were evolved.

Arguably the best example of a good scientific theory is Newton's theory of gravity. It may come as a surprise that although this is an excellent predictive and descriptive theory, it is rather a poor explanatory theory. It is a poor explanatory theory in the sense that Darwinian theory of evolution or the kinetic-molecular theory of gases are excellent explanatory theories. We simply have a very poor understanding of the mechanism of gravitational attraction.

Indeed, the virus theory of poliomyelitis is a good explanatory theory, whereas the "beautifully systematized laws of mechanics are not" (Harre, 1971). On Harre"s account the kinetic-molecular theory of gases is an explanation, or *generative mechanism* of the behaviour of gases. However, it follows the paradigm of the virus poliomyelitis, and not the paradigm of Newton's force formulation of mechanics (in spite of its mathematical nature). In this sense Newton's theory of gravitation is a poor explanatory theory. Science, it seems, consists of both kinds of theories.

Does this imply that Newton's theory of gravity is no more explanatory than the algorithms (rules) of the Babylonian astronomers were? In a sense that seems to be the case. However, Newton's theory is a complex network of interconnected laws and definitions, it has diverse connections to otherwise disparate sets of phenomena, and has great predictive and problem-solving powers. When scientists speak of "explaining" an event or a problem involving the motion of a planet, for example, they refer to the powers that reside in the Newtonian theoretical framework. They do not imply that Newton's theory of gravity "explains" events by way of an underlying mechanism.

Most explanatory models (theories) involve both inductive and deductive processes. See if you can identify the inductive and deductive processes associated with the following theories:

1. Galileo made certain measurements relating to the motion of a metallic sphere along an inclined plane .

   Textbooks tell us that Galileo inductivel**y** generalized, much like we do in physics labs, from a few "tries" to the law of free fall (distance covered by a freely falling body is proportional the square of the elapsed time).

   However, according to Stillman Drake, the world's leading Galileo scholar, Galileo also seems to have made a number of hypotheses about the nature of accelerated motion, including the correct one, namely that *speed is proportional to the elapsed time*. From this he showed mathematically that one of the consequences must be that distance is proportional to the square of the elapsed time. What is surprising, though, is that he wrote down his hypotheses before he made measurements to test this consequence!

2. Newton attempted to "explain" three classes of apparently unconnected phenomena: the motion of the pendulum, the phenomenon of the tides, and the elliptical orbits of the planets.

He found that to accomplish that he needed only four laws, three laws of motion and the inverse force law of gravitational attraction.

3. John Dalton is generally credited with the formulation of modern atomic theory around 1805. He had been interested in meteorology, and especially in the problem of why the gaseous constituents were so well mixed despite the differences in their specific gravity. Dalton found in reading Newton's Principia the "proof" that gases must behave according to Boyle's law if it is assumed that the force between particles is repulsive in proportion to the distance between them. Next, he accepted the then current caloric theory that held that each particle is surrounded by a sphere of caloric fluid that was endowed with the quality of self-repulsion. Thirdly, he assumed (based on his own experiments) that individual particles of gas must differ in size from those of another gas. Dalton then concluded that the mixture of components of the earth's gases was now explainable because mutually-repulsive of several different sizes would not be in equilibrium in a stratum. This work led him to fundamental and revolutionary concepts of the chemical atom, atomic weight, and the Law of Multiple Proportions. Notice, however, that every one of the steps he used was either factually wrong or logically inconsistent (see Holton, 1980, pp. 385-386).

In each of the generalizations above we decided that human imagination was able to find generalizations from which it is possible to make deductive inferences. For example, from Newton's laws we are able to "deduce" the periodic motion of a pendulum as well as the elliptical motion of the planets. From the theoretical framework of atomic theory and spectroscopy we can "deduce" that the outer atmosphere of the sun contains helium.

The attempt to deal with the problem of induction and explanation in gaining scientific understanding gave rise to the various philosophies of science since the time of Hume. It also generated the fundamental questions of epistemology (theory of knowledge) and ontology (the status of this knowledge) that philosophers of science still discuss today. Examples of such questions as: "What is the relationship between observations and theory?" and "Are scientific laws, models, theories real, or are they merely human inventions?"

Before we discuss the reasoning involved in scientific inquiry in some detail we should remind you of the distinction between inductive and deductive reasoning. It will also be important to differentiate clearly between empirical truth and logical validity (sometimes called logical truth). The work of the British philosopher and logician John Stuart Mill (c. 1840) stands out when discussing the major attempt to reinstate induction. Mills philosophy of science is an outstanding example of the inductivist's point of view, epitomized by Karl Pearson in the "scientific method. in turn.

For example, it is known that Einstein's GTR can explain all that Newton's gravitational theory can (the tides, free-fall, the motion of the planets). However, the theory can explain much more than Newton's theory can: it can explain black holes, for example. What you must remember is that even if the theory of general relativity had predicted the wrong value for the bending of light in the vicinity of the sun, the logical reasoning itself from the theory would have been considered impeccable.

It is, of course, logically possible to have false premises and still come up with the correct answer. Does this mean that Einstein GTR could contain a false premise even though the theory predicted the amount of bending of light? Yes, it does. How can scientists be sure about the soundness of a theory? Simply by testing as many significant predictions as possible. If, indeed, the GTR had failed to predict the correct value of gravitational red shift or the special precessional motion of Mercury (that Newtonian theory could not explain) it would have failed as a good physical theory. But the deductive reasoning from the theory would have been left intact.

Can false premises lead to true conclusions? Here is a simple example of reasoning from false premises to true conclusion, due to Aristotle:

Premise 1: All stars are bodies that shine steadily.

Premise 2: All planets are stars.

Therefore: All planets are bodies that shine steadily.

Can you make up an argument that leads from false premises to a true conclusion? Let us look at some examples of scientific reasoning: "What sort of reasoning is it that allows us to make generalizations that are more comprehensive than the facts on which they are based?" (The word *generalization* can be seen as *theory*, like Newton's theory of gravitation or Darwin's theory of evolution.) As Gerald Holton, a leading historian of science has put it: "At the least it has become clearer in our day that the pursuit in science is itself not a science" (Holton, 1980, p. 386).

### *Karl Popper and the Problem of Induction*

The most famous contemporary philosopher of science is arguably Sir Karl Popper (b. 1902). Popper argues since we can never observe all possible cases, we can never "prove" a theory to be true, but if a theory or hypothesis fails to survive a test we can **reject** that theory or hypothesis. Therefore we must construct scientific theories by the method of eliminating false ones. The task of science, then, is to imaginatively invent theories of a high degree of falsifiability. In fact rational thinking itself for Popper consists in detecting errors, in eliminating them, and in learning from them. The type of argument Popper is offering, according to formal logic looks like this:

if H then C

Not C

Therefore not H

As far as scientific processes resemble formal logic Popper's method of falsification is valid: although a *theory or hypothesis can never be conclusively proved, it can be conclusively falsified*. As Hume pointed out, the piling up of favourable instances in inductive reasoning can never lead to the complete confirmation of a universal statement. But only one negation of the consequent necessarily would lead to the rejection of a hypothesis or a theory. According to this view one example of a levitating heavy object (on the surface of the earth) then would topple Newton's gravitational theory!

What does Popper recommend that scientists do in the face of the failure of induction? His radical proposal is that scientists should consider evidence only to the extent it tends to falsify general statements. He argues that systematic growth in science can only occur when science treats ideas as falsifiable.

This proposal is at the heart of his famous Demarcation Principle that allows us to decide whether a hypothesis or a theory is scientific or non-scientific. Unless a putative scientific theory suggests some test that could lead to its refutation, then it is not scientific theory. For example, "theories" like astrology and psychoanalysis, are not scientific theories because there is virtually no test that could be applied that might refute them. Psychoanalytic theories and astrology are able to explain any outcome and are therefore virtually without predictive powers. Similarly, biblical creationism cannot be presented as a scientific theory of the origin of the world because, as a matter of faith, based on biblical authority, it, too, is irrefutable.

**Protecting Theories**

The philosopher of science who tried to explain why scientists in general are not Popperian, was the British -Hungarian Imre Lakatos. He said that scientists simply do not consciously attempt to invent theories of a high degree of falsifiability. Rather, he argued that such high-level theories as Newton's gravitational theory should be thought of as a *core theory*. Core theories are "protected" by a layer of auxiliary theories.If an experimental result cannot be explained in the light of a theory scientists do not rush to reject the core theory. Rather, they tend to adjust the protective belt of auxiliary theories in order to fit the experimental result to the core theory. If scientists aimed at establishing theories with the purpose of falsifying them, theories would not survive very long. Theories must be given ample time to protect themselves. Lakatos recognized this and said: "We must treat budding theories leniently".

We have already mentioned that when it was discovered that the motion of Uranus could not be explained by Newtonian physics astronomers protected the core theory of gravitation by looking for a new planet. Moreover, when Priestly claimed that phlogiston must have negative mass it was not considered a serious blow to Newtonian physics. Finally, when it was discovered that electric forces attract as well as repel, this was not thought of as an instance of falsification of Newton's gravitational theory. A number of theories dealing with electric and magnetic forces were devised, keeping gravitational theory intact.

However, it is not always possible to protect a core theory. Toward the end of the 19th century it became clear that Newtonian physics could not deal with certain experimental results (Michelson -Morley experiment showing the constancy of the speed of light and certain asymmetries inherent in electromagnetic theory). When it was clear that no auxiliary theory could patch up Newtonian physics to reconcile it with such findings Newtonian physics was replaced by Einsteinian physics. The historian of science who had a lot to say about this sort of radical change is Thomas Kuhn. We have already discussed his ideas in the previous chapter.

## Philosophies of Science

We will now take a brief look at some of the key philosophies of science that attempted to deal with the questions that the fundamental problems of induction and explanation generated. We will then discuss to what extent science textbooks and science teachers consider the findings of the philosophy of science.

These two early philosophies of science can be seen as the progenitors of a host of philosophical schools in science. These can be roughly be placed into two major categories: The empirical-inductive and the constructivist-imaginative. Philosophers in the first group generally believe in the primacy of data and in a specifiable scientific method. The second group, on the other hand, insist that data are dependent on our theoretical background and argue that the passage from data to generalizations (theories) cannot be pinned down by method. This passage, it is thought, is utterly dependent on the human imagination and the prevalent world view of the times. We will look at these two groups in turn.

### The Empirical-Inductive Philosophies of Science

The foundations of empirical-inductive science can be traced back to Francis Bacon in the 16th century. Bacon believed that we can read *the book of nature* and arrive at large scale theories by random observation and experimentation by looking for patterns and generalizations. This is the process of inductive reasoning

### Logical Positivism

Following in the footsteps of Bacon and building on his ideas, August Comte (c. 1820), argued that science was characterized by applying a specifiable method that guaranteed success, even in the face of the failure of induction. The method begins with specific data that produce ascertained facts by way of establishing experimentally confirmable laws. Comte was the founder of what we today call the positivists philosophy of science.

Karl Pearson was a statistician who published an influential book about the nature of scientific inquiry in 1892. The book was entitled *The Grammar of Science* and can be seen as the original statement of what is known as the "scientific method". He summarized the empiricist-inductive view of science very convincingly. It can be argued that the notion of scientific method as described in his work, has become taken for granted by many practical, every-day scientists and science educators well into the middle of this century (Stinner, 1989).

Pearson believed that science is essentially an empirical-inductive enterprise that had four characteristics:

1. Science has achieved a superior kind of truth.
2. Science was characterized by inexorable progress.
3. Science was in the possession of the only method of interrogating nature, namely the empirical-inductive method (the "scientific method").
4. This method could be simply described and easily taught.

You should readily recognize this picture of science: to a large extent it is still held by the general public, and is present in our science teaching.

**The Constructivist-Imaginative Philosophies of Science**

William Whewell (c. 1840) recognized that it was not possible to identify 'relevant facts' without assuming a background theory. A background theory, like Newton's gravitational theory, is not based on 'systematic analysis of data', as his famous British contemporary, J.S. Mill, claimed (and later enshrined in Karl Pearson's book The Grammar of Science). A fully-developed theory, like Newton's theory of gravitation or the kinetic-molecular theory of gases, of course, does not come easily and immediately. The question-and-answer procedure involves experiments, often using data that are selected on the basis of an incomplete theoretical background. The struggle to achieve a conceptual basis for such a theory involves a continual ordering and re-ordering of questions in response to experimental results and corresponding changes in deciding what the appropriate physical quantities must be that will appear in the definitions and the laws.  A specifiable scientific method of the kind Pearson described, it is argued, simply cannot accommodate this kind of scientific thinking.

Much like Whewell did, the "new" philosophers (Kuhn, Laudan, Hanson, Lakatos) have argued that scientific facts are meaningful only in the context of a theoretical background.  Like Whewell, they advocate the study of the history of science in studying scientific activity, and reject formal logic as a primary means of analyzing science.  Moreover, they emphasize continuing research programs together with on-going criticism as the core activity of science.

## Implications for Science Teaching

Guidelines, textbooks and common practice tend to present science and the "processes" of science essentially as inductive method.  They seldom discuss the question of what scientific induction is, and what the problems of induction are as we have outlined them in this chapter.

We have argued that much of science as represented by "inquiry" and "process" is the discredited scientific induction in disguise. It is puzzling that science textbooks fail to discuss the problem of induction in any detail.

In a classroom science, teachers could begin the discussion of scientific induction with examples such as the ones suggested above.  The first example can be discussed in grade 8/9.  The second one is idealfor discussing the mechanical procedures we use in elementary physics experiments in high school.  These experiments involve the proportionality statements between dependent and independent variables.  The third example deals with one of the great achievements of science.  A historical presentation of how Newton used intuition, imagination and experimental confirmation to arrive at his great system of laws and definitions, roughly along the lines discussed in Harvard Project Physics. This splendid story of high-grade science should convince the student that high-level theories cannot be arrived at by way inductive thinking of the Pearsonian kind.  The case of discovering Helium in the sun is a complex and fascinating story involving chemistry, spectroscopy and astronomy. Dalton's story of how his reasoning and his assumptions, although either factually wrong or logically inconsistent, still led him correctly to the modern atomic theory must be the most compelling argument for crediting the human imagination and not an inductive-scientific method.

Finally, science teachers and textbooks explicitly or implicitly tell students that there is/are scientific method(s) that involve mechanical-inductive procedures along the lines suggested by Pearson one hundred years ago. Rather, we should show students that indeed many elementary investigations proceed along those lines. However, most high-grade scientific activities, such as Newton's mathematical description of the motion of the planets, Lavoisier's researches that led to the discovery of oxygen, and the work of Crick and Watson in producing the DNA model, cannot be pinned down by a specifiable method.

Moreover, experiments students perform in classrooms are of the type "To verify Newton's second law of motion". The format the students follow is arguably based on a modern version of Pearson's scientific method (See appendix 2). It is recommended, then, that teachers teach toward clarifying the nature of induction, consciously incorporated in the curriculum. Our discussion of deduction in science suggests that it is equally important to incorporate into the curriculum how scientists frame explanatory theories and show what their strength and weaknesses are.

Generally science textbooks and science teachers implicitly stress the deductive nature of scientific theories. The student first becomes acquainted with the deductive formulation of theories when he reasons this way:

All metals are conductors of electricity

Copper is a metal

Therefore copper is a conductor of electricity

Later, in high school, the students learn Newton's laws of motion by way of the finished product of mathematical formulation. From these he reasons deductively while solving problems of motion.

The first example is typical of what is perceived as scientific explanation by the junior high school student. To the question "why are metals good conductors?" the teacher may offer a textbook answer based on the electron-model of conduction. The teacher might say: "You will learn this later in high school physics". In either case the student is likely to be baffled and loses interest.

Our second example is typical of what is perceived as scientific explanation by the senior high school student. S/he has at their disposal the laws of motion from which he/she is able, by simple mathematical deduction, to solve "type problems". Neither student, however, is generally aware of the fact that h/she is engaged in deductive thinking nor of how such deductive systems are arrived at. Nor are they aware of what would count as an explanatory theory that makes deductive reasoning possible in each case and what features the two theories have in common and what sets them apart.

In our first example we should make the student aware that the statement; all metals are good conductors of electricity (and heat), does not rest on an inductive process of reasoning based on investigating as many metals as possible. Rather, it is based on a rich theoretical framework diversely connected with electric theory, thermodynamics and quantum theory. This then is a good explanatory theory.

While we cannot give the student a detailed explanation we can still indicate this theoretical background on a lower level. In our second example, calculating the distance an object falls, using the equations of kinematics, could be arguably be called "deductive". In what sense, however, do we reason deductively when we find the expression for the period of the pendulum? Finally students should understand that Newton's theory of gravity is a poor explanatory theory despite its awesome powers of prediction.

## FOCUS QUESTIONS

**Note to students**: *These questions are to help you indentify important ideas in the chapter. They will also be the focus of class discussions. You do not need to hand them in, but if you can discuss them, you will have a reasonable grasp of the ideas in the chapter. It would be helpful to you if your cooperative group discussed them before each class*.

1. First differentiate between inductive and deductive reasoning in general then discuss the relationship between inductive and deductive reasoning in science. (See appendix 2) Give several clear examples.

2. The following are examples of statements/arguments. For each one decide what kind (deductive, inductive, statistical, logical, other) of argument it is and whether it is *valid*. In each case, give a reason for your choice.

   a. The earth is larger than the sun. The sun is larger than the moon. Therefore, the earth is larger than the moon.

b. If you take vitamin C regularly, you will catch fewer colds.

c. If John smokes, John will have a reduced life expectancy. John smokes. Therefore, John will have a reduced life expectancy.

d. If a piece of wire is pounded it will heat up.

e. If Einstein's theory of relativity is true, then light must bend in a gravitational field. It is the case that light bends in a gravitational field. Therefore, Einstein's theory of general relativity is true.

3. You can easily derive Galileo's law of free fall from Newton's second law. Does that mean that this is a *deductive* argument? If so, in what sense is it deductive? If not, what kind of reasoning is it?

4. Consider the following argument, and comment on its

All wooden things are conductors.

All metals are wooden.

Therefore, all metals are conductors.

5. Discuss the following statements in terms of logical truth and empirical truth:

a. The sun will rise tomorrow.

b. If I drop this hammer it will fall toward the centre of the earth with a nearly constant acceleration.

c. 2+1= 3

d. The internal angles of all triangles add up to $180^{o}$.

7. What did Alfred North Whitehead's mean when he said: "Science went right ahead, knowing that Hume had refuted it."

8. How did Popper attempt to solve the problem of induction? To what extend do you think was he successful?

9. Consider the following in terms of Popper's falsification criterion by asking the question, what empirical discovery would considerably weaken each?

   a. The periodicity of the elements as expressed in the periodic table

   b. Einstein's general relativity theory (see example in this chapter)

   c. The theory of evolution

   What would count as a convincing example of refutation in each case?

10. Give examples of scientific statements that cover the whole explanation/prediction asymmetry.

11. Distinguish between the <u>empirical-inductive</u> and the <u>constructivist-imaginative</u> philosophies of science.

12. Use the ideas of "core theory", "protective belt", and "auxiliary theories" to show how a theories like Newton's theory of gravitation and the theory of evolution can survive repeated challenges from other "theories".

13. We tell students that atoms are made up of electrons, protons, and neutrons. But what evidence is there for the "existence" of these sub-microscopic particles?

## Cooperative Learning Activity

**To the student**: The purpose of this activity is to bring about an exchange of ideas among students. You will be given between 10 and 15 minutes in class to meet in your cooperative group to discuss the issue and prepare to report back to the class on your group conclusions. Select one of the following for this activity.

a. Sir Karl Popper says:

> The belief that science proceeds from observation to theory is still so widely and so firmly held that my denial of it is often met with incredulity....Twenty five years ago I tried to bring home the same point to a group of physics students in Vienna by beginning a lecture with the following instructions: Take pencil and paper: carefully observe, and write down what you have observed!" They asked, of course, what I wanted them to observe. Clearly, the instruction "observe" is absurd. Observation is always selective. It needs a chosen object, a definite task, an interest, a point of view, a problem (Popper).

Suggest an appropriate activity that might convince young science students that they "see" with their ideas.

Scientists seem to reason inductively from a set of data to a generalization. Then they reason deductively from this generalization to make predictions. Give examples of this process in physics, chemistry and biology.

b. Judge William Overton, passing judgement on the Arkansas law "Balanced treatment for creation-science and evolution science act" of 1981, ruled that creation science is not genuinely scientific since it fails to meet what Overton calls the five essential characteristics of science (see C. Ray: "Breaking free from dogma: philosophical prejudice in science education" *Science Education*, 75: 87-93.) These criteria are:

a. It is guided by natural law:

b. It has to be explanatory by reference to natural law;

c. It is testable against the empirical world;

d. Its conclusions are tentative, that is, they are not necessarily the final world;

e. It is falsifiable.

In his article Christopher Ray tells us that this characterization of science was based on the testimony of working scientists and philosophers of science. Moreover, he points out "the lack of tentativeness" in Overton's assertions about the field which he says should be tentative!"

Criticize these criteria. For example, using these criteria we might have to exclude the social sciences from th

# Chapter 5

## Mathematics and science; The Contexts of Inquiry in Science

The contexts of inquiry: A historical review

The contexts of inquiry in physics:

The context of questions

The context of method

The context of experiments

The context of method

The context of problems

The context of history

Aristotelian physics

Galilean Physics

Newtonian physics

Einsteinian physics

**Mathematics, Newtonian mechanics, and the teaching of elementary physics.**

Most physics teachers probably accept the fit between mathematics and the world as an *absolute presupposition* that is beyond question. Others seem to believe that there is a match because our mathematics describes only the *idealised* world of frictionless surfaces and massles pulleys. Einstein, for example, responded to this puzzle with a famous epigram:

As far as the propositions of mathematics refer to reality, they are not certain...and as far as they are certain, they do not refer to reality. (quoted in Little, 1980)

Einstein's comment sets the stage for our investigation of the relationship between mathematics and how we describe the world in elementary mechanics. We will attempt to give a historical account of the puzzling nature of the relationship between mathematics and physics, but only to the extent this is shown in pre-Newtonian and then in Newtonian physics of mechanics. By restricting ourselves to the physics of elementary mechanics we will greatly simplify our task as well as ensuring that the arguments and the ideas used are suitable for discussion in a secondary physics class.

We will begin by giving an account of how mathematical and scientific thinking emerged together during the seventeenth century. The mathematical thinking of Galileo will be discussed, who arguably initiated the mathematization of the world. This is followed by looking at Newton's style of thinking that has become the *paradigm* example of how mathematics relates to the world and how mathematically formulated theories in physics should be established. We will then look at some of the persistent fundamental problems concerning the relationship between mathematics and the world that surfaced already in Newton's time. Finally, we shall investigate the pedagogical problems associated with the teaching of physics by way of the *finished product* of analytical mathematics.

**Mathematics and physics: Galileo**

Let us look at the first great problem of mathematical physics, namely the problem of free fall, from a Galilean point of view (as recorded in *Two Sciences,* Book III). Bodies were thought to accelerate because at each new instant of fall there is a new measure of attraction (Galileo, 1954, Book III. p. 165 ). Thus every new measure of attraction confers a new degree of movement. For example, looking directly at freely falling bodies, it is not at all clear that the speed changes in any mathematically describable fashion. In fact, it looks as if a speeding-up period were only an initial event.

"Diluting gravity" by using an inclined plane, however, suggests that motion is such that the speed is changing in some regular fashion. We cannot measure the speed at a given moment (the instantaneous speed); we can only relate the distance travelled to the time elapsed. After many "runs" we can establish that indeed distances travelled are to each other as their corresponding times squared.

Galileo began his theoretical work with *thought experiments* to clarify such concepts as average speed and to delineate clearly the limit of his mathematics base on Euclidean ratios. He then proposed a number of *working hypotheses*, seeking a general rule for uniform growth of distances, times and speeds. Galileo at this point seemed to have used a selection process that depended on two conditions being satisfied:

1. The *necessary condition* that a candidate hypothesis be expressible in terms of Euclidean geometry and ratios,

2. The *sufficient condition* that a candidate hypothesis be *physically meaningful*, i.e. empirically testable. He says:

For anyone can invent an arbitrary type motion, and discuss its properties;...but we have decided to consider the phenomena of bodies falling with an acceleration such as that *actually* (italics mine) occurs in nature and to make this definition of accelerated motion exhibit the essential features of observed accelerated motion....Finally ...in following the habit and custom of nature herself in all her various other processes, to employ only those means which are the most common, simple and easy. (Galileo, 1954)

Galileo's objective was to find a consistent set of ratio-relations that satisfied both the experimentally established relationship $d^2 / d_1 = (t_2 / t_1)^2$ and the mean value theorem (see Appendix).

Studying the hypotheses, we see that $H_1$ leads to a contradiction with the definition of constant speed. $H_2$ looks more reasonable, but does not seem to lead to a proportionality statement that is accommodated by Euclidean ratios and must therefore be discarded. $H_3$, however, leads to the correct ratio between distance and time. Note that the argument here is based on one physical criterion and the conclusion is reached on the basis of mathematical reasoning alone. Moreover, $H_4$ seems to be compatible with $H_3$ because from it follows mathematically that $(d_2/d_1)=(t_2/t_1)^2$.

We now have a consistent set of ratios because only these are reconcilable with the experimentally established result that the distance covered is proportional to the square of the elapsed time, and with the mean value theorem (see Appendix ).

But how are we to interpret physically such quantities as $v^2$ and $d^{1/2}$ ? Galileo asked this question, so we certainly should ask it of our students. Even if we rewrote the relationship from $d \sim v^2$ to $d^{1/2} \sim v$, how would a speed of v go about adjusting itself to a quantity through which it had already passed? It seems that in order to describe uniform motion and identify it with free fall we have to eliminate cause as a necessary concept, but at the cost of having to find a physical meaning for such quantities $v^2$ and $d^{1/2}$.

Finally, we should remind ourselves that we in fact still cannot experimentally show that continuous change is associated with changes we can measure only in discrete units. At this point we seem to be right back to one of Zeno's paradoxes.

**Complex Problems**

Galileo went on to investigate more complex motion. He succeeded in describing projectile motion. The greatest triumph of the mathematical approach to describe phenomena, by his own admission , was realized in the successful description of projectile motion.

The actual motions in the world were, however, too complex to yield to Galileo's mathematics which was firmly rooted in Euclidean geometry and ratios. Terrestrial motions such as a swinging pendulum, colliding billiard balls, and the motion of a metallic sphere freely falling in a liquid and celestial motions such as that of the planets in elliptical orbits, had to await the description of the synthetic mathematics of Newton (based on the findings of the infinitesimal calculus).

A close examination of these motions clearly shows the need for the idea of function as well as the calculus to solve problems of this complexity. The necessity to deal with the concept of changing acceleration (the change of a change), and the need for a method of counting the effects of an infinite number of contributions, lead to the notion of function and to the notion of limit, and ultimately to the differential and the integral calculus.

Galileo clearly recognized the limitation of his mathematics to solve such problems as a sphere falling in a resisting medium (Galileo 1954) Indeed, the mathematical description of the motion of the a metallic sphere can be thought of to represent a problem that is at the limits of the Galilean ratio-type *cum* Euclidean geometry method of solving problems in physics.

**Mathematics and physics: Newton**

Newton gave the seventeenth century a consistent, all-encompassing picture of a *mechanical* world that could be described and understood through the power of mathematics. Phenomena, such as free fall and the motion of the planets, were governed by *laws*, expressed in mathematical language. Both terrestrial and celestial phenomena were seen as *law-like*, in some sense of law-like.

It required only three laws of motion in conjunction with his law of universal gravitation to reveal at once the physical significance of Kepler's laws of planetary motion, explain the origin of the tides, and give an account of Galileo's free fall. Moreover, the unprecedented success of the *Newtonian style* of thinking, *in which mathematics is applied to the external world as it is revealed by experiment and critical observation (*Cohen, 1981) has become our paradigm example of how theories in physics should be established.

When discussing Galileo's physics one can still, more or less, manage to deal with his entire work on motion in order to get a sense of his scientific as well as his mathematical thinking. This is almost impossible with Newton, unless one is prepared to spend years of immersion in the world of the *Principia.*

We will give a brief account of only one important, and often neglected aspect of his physics: his struggle to establish the notion of force as a unifying concept of motion. Even a modest attempt, such as this, however, turns out to be a challenging as well as a rewarding task.

The central problem that Newton faced was to extend Galileo's kinematics and to answer the question "Why do bodies move?" In other words, he responded to Galileo's challenge to find a *causal mechanism* for motion, expressed in the language of mathematics.

Newton first turned his attention to the problem of free fall. Free fall provided one sense in which the notion of force as a causal principle was to be understood. The notion of force, however, had to be reconciled with how it was used in two other senses: force as a measure of motion, and force as a measure of change of motion.

Newton had available three distinct sets of observations that could be connected to three distinct meanings of the notion of force. One set was connected to *free fall*, as demonstrated by experiments with the *pendulum*. Another set of observations were connected to the motion of a *conical pendulum*. Finally, a third set of observations were based on collision experiments with wooden balls used as pendula. In the first case we are dealing with *inertia* (Atwood's Machine and Fletcher's Trolley experiments were still in the future), in the second case with forces associated with the change of direction of a mass (what is still commonly, but wrongly, referred to as "centrifugal force"), and in the third case we encounter the problem of how to relate the notion of a force to *impact.*

Newton, therefore, had to find a consistent dynamics to describe three distinct classes of observations: accelerated motion in a straight line, the "acceleration" of a body moving with a constant speed but changing direction, and finally the motion involved during collision. The first was associated with the quantity $\mathbf{ma}$ , the second with the quantity $\mathbf{m\,v^2/r}$ and the third with the quantity $\mathbf{m\,v}$.

The sorting out of these various meanings, according to Westfall, was a difficult task for Newton. More especially, Newton seemed to have had great difficulty in getting rid of the idea of *centrifugal* (center-fleeing) force in describing a body in circular motion. Clearly, the thorny problem of the meaning of force in circular motion could not be solved until he managed

to extricate himself from thinking in terms of an *equilibrium of forces*.

It seems that Newton finally solved this problem in two stages. First, he compared the force involved in rotating an object at a constant tangential speed to the equivalent force in accelerating the same object linearly to the same speed as the rotating object. This analogy gave him the correct result

$\mathbf{a = v^2/r}$. However, until he was able to think of the force as *center-seeking*, rather than *center-fleeing*, his dynamics could not be applied to the problem of describing the motion of the planets. Both Cohen and Westfall argue that Newton learned from Hooke how to decompose curved motion into an inertial component and center-seeking (centripetal) component. They both agree, however, that it was Newton's supreme mathematical imagination that saw the connection between the centripetal force and the **inverse square** and **center-force law.**

In laying the foundations for his dynamics Newton invented the calculus. Continental mathematicians, like Euler, Lagrange and Laplace, however, quickly departed from Newton's *synthetic method* of the *Principia* (Euclidean geometry and ratios, and conic sections) and developed a very sophisticated *analytical mathematics*, based on Leibniz's original works and notation. The *analytical* mathematics of the continental physicists turned out to be superior to the *synthetic* mathematics of the *Principia* in clarifying the fundamental concepts such as inertia, acceleration, force, momentum and generalizing Kepler's laws of motion. This essentially mathematical activity culminated in the elegant and powerful Lagrangian formulation of dynamics that included the conservation laws of momentum and mechanical energy.

**Some fundamental problems**

The calculus, however, raised fundamental problems concerning the relationship between mathematics and the world. Many of these are still with us. In Euclidean geometry the *infinite* and the *infinitesimal* are deliberately excluded by banning any reference to number. Zeno had argued that if time were a row of successive instants then motion would be impossible. He also asked if it was at all possible to add up *infinitely many infinitely small things.* He thus raised questions about the concept of *continuity*, infinitesimals, and infinity that are still with us.

In what is regarded as the first text book on calculus (published in 1698) L'Hospital stated that two quantities differing by an infinitesimal can be considered to be equal! But it was the dubious notion of the fractional quantity infinitely close to zero, **but not equal to zero,** that lay at the foundations of the calculus. Nevertheless, the calculus was the golden key that opened the doors to all the secrets of mechanics and dynamics. The shaky mathematical foundations on which it was built, however, were happily ignored by most mathematicians and natural philosophers. Leibniz is said to have referred to infinitesimals as "useful fictions" and Bishop Berkeley referred to them as "ghosts of departed quantities" and added that anyone who could believe in them need not be "squeamish about any point in divinity" ( quoted in Steen, 1978).

The question, therefore, that mathematicians did not seriously investigate in the 17th and 18th centuries was "How can we get rid of the infinitesimal but still save the superstructure of the overwhelmingly successful calculus?" Arguably it was precisely the overwhelming success of the calculus in solving the most difficult "puzzles" generated by Newtonian physics that prevented a serious attempt to answer this question until the second half of the 19th century. It is interesting to note that contemporary Non Standard Analysis has, by all accounts, successfully reinstated the infinitesimal on firm mathematical ground.

But there are still problems. When we add experimentally obtained quantities, the result is not identical with the arithmetic operation of addition. This is so because the numbers normally assumed in the mathematical formulations of physics are *real* numbers, while the numbers used to represent lengths identifiable by laboratory measurements are the *rational numbers.* Now, we know that the set of *rational numbers* are denumerably infinite, while the set of *real numbers* are non-denumerably infinite. Therefor the mathematics of physics and the domain of measurable lengths are not strictly *isomorphic.*

This puzzling situation suggests that perhaps it is possible to have mathematically incompatible but empirically equivalent theories. For example, in Newtonian physics our assumption that space and time are continuous produces the well-known equations of the differential calculus. It is known, however, that one can find equivalent equations based on the assumption that space and time are dense but *discontinuous*. The two approaches then will yield theories which are mathematically incompatible, but empirically equivalent. That is so because our laboratory measurements are always expressed in terms of *truncated rationals.* Therefore, it is impossible to measure 2 or with a "magic meter stick", however accurate. Thus Pythagoras' *incommensurables* are still haunting us today.

**Implications for the teaching of physics**

We have seen how Galileo historically matched his mathematics with the phenomenon of free fall. He moved freely between logical arguments, thought experiments, working hypotheses, and experimental confirmation. Similarly, Newton moved imaginatively between a select number of experimental results (Galilean free fall, the conical pendulum, collision between hardwood spheres) and geometric (Euclidean geometry and conic sections) and mathematical (Fluxions) arguments. In addition, he *consciously* aimed at constructing a deductive system in which Galileo's kinematics would be a special case.

The conventional text book account of how Galileo discovered the law of free fall is clearly a reconstruction of the historical account, often to fit the demands of what textbooks writers *implicitly* or *explicitly* call "the scientific method". This way of presenting the discovery is an oversimplification at best and it implies that Galileo, like today's high school student, tabulated experimental results and then expressed the relationship between the variables (distance and time) as proportionality statement. Moreover, textbooks generally suggest that Galileo timed the rolling of the metallic ball and *inductively* found the value of the proportionality constant in the relationship $d = k\,t^{2.}$ Our brief historical discussion of Galileo's discovery of free fall, however, suggests that we should tell the splendid *story* of the first great adventure in mathematical physics more compellingly than the conventional textbook account does.

High school textbook accounts of Newton's laws of motion generally fail to give even a cursory discussion of how these laws were formulated. The laws are often presented as if they were self-evident and came full-blown to the creative mind of Newton (shortly after the apple collided with this head). Some textbooks of elementary physics go further and suggest that Newton tested his second law along the lines we test it in high school experiments, suggesting that he *inductively* arrived at these laws. Our brief discussion earlier of the route Newton followed in unravelling the complex notion of *force* mitigates against simply presenting the student with the a mathematical statement of the laws or asking them to *inductively* arrive at laws by experimentation.

It is clearly not possible, nor in fact desirable, to guide the student through a deep study of Galileo's *Two New Sciences* or Newton's *Principia* in quest for a historical understanding of how these discoveries and conceptualizations were made. It is not necessary to recapitulate the struggle of the creative science genius in science teaching. However, students, should be made *aware* of the personal struggle as well as the role mathematics played in arriving at conceptualizations in physics. We must do this not only for the sake of imparting a fine sense of science history but also for reminding the student that science is a human endeavour not describable by a specifiable method.

**Conclusion**

The mathematization of the world was a great success in the hands of physicists. Mathematical intuition in matching mathematics with physical phenomena is clearly required in successful theory building in physics. Indeed, as we have tried to show, in high-grade theoretical activity, the mathematics itself will allow one to think *beyond the physics.* The physicist Ernst Mach once remarked:

The power of mathematics rests on its evasion of all unnecessary thought and on its wonderful saving of mental operations. (quoted in Dyson, 1964)

The efficacy of mathematics and the trust we place in its considerable powers in aiding our understanding of the world, however, can be pushed too far. We may be treading on dangerous ground here with respect to *sound theory* building as well as the *teaching of elementary physics*

With respect to *sound theory building* in physics Edward Witten, a rising young *theoretical physicist* said recently, when talking about his mathematical models in *superstring theory:*

General relativity is a theory where the concepts came first, and since Einstein everyone is trying to imitate it. ...Superstrings, unfortunately, is more a mathematical instead of a conceptual theory. Strings were *invented by chance* (italics mine) rather than by being deduced from any logical framework. The problem with superstrings is that we don't understand it conceptually yet. One of the things I'm trying to do is to provide the conceptual framework that's still missing. (quoted by Ed Regis, 1987).

If Witten's picture of what theoreticians are doing at the foundations of physics is correct then Newton's and Einstein's style of interrogating nature has given way to mathematization, largely disconnected from the world. It might be that we are again, as we were in the 17th century, confronting the kind of problems and conceptualizations that signals the necessity of finding a new kind of mathematics. Perhaps we will find an equivalent to Goedel's *undecidability theorem* in physics, that might tell us that physicist's quest for the mathematical form of a *theory of everything* is futile.

With respect to the *teaching of elementary physics,* the British science educator William Whewell said 150 years ago that initiating instruction with the *finished product* of analytical mathematics (algebra and calculus) we would inevitably deduce "from principles of combination of symbols of number and quantity, rather than by reasoning...".Whewell, of course, is simply reminding us that arithmetic processes and Euclidean ratios were the foundations for the study of algebra and a thorough knowledge of geometry and conic sections were a prerequisite to the study of the differential calculus. For example, rather than present Newton's second law of motion as F = ma, and have students solve problems by memorizing an *algorithm,* we should discuss the notion of force roughly along the lines presented in this paper.

In Whewell's time, and still today, in the exposition of material, text book writers as well as physics teachers, tend to strive for economy of expression and clarity of thought. These are supposed to be synonymous with the explicit mathematical and symbolic formulation of a topic. However, we have seen that what precedes a finished product in physics is *precisely* verbal argumentation that involves *thought experiments, geometric arguments,* and logical argument. If Whewell is right, then we must set contexts that engage our students in *re-creating* concepts outside the grip of *finished* mathematical formulations we find in text book-centered teaching.

In our science teaching we seem to assume that if the student is able to solve "type problems", or the textbook exemplars of a given topic, then he must have a good grasp of the fundamental principles and concepts involved in both the subject matter and the relevant mathematics. Physics teachers, however, know that this is not necessarily so. Our discussion then suggests that we should supplement the conventional approach with both *pre-algorithmic* and *post-algorithmic* activities. The *pre-algorithmic* stage, our discussion suggests, should involve the explication of fundamental concepts by way of such activities as the construction of thought experiments, the discussion of intuitive physics, and the selection of hypotheses that may involve geometric, logical and even extra-logical considerations. The *post-algorithmic* stage should deal with contexts and problems that help the student to *generalize* and gain a firm understanding of concepts, laws and theories, far beyond the mere memorization of algorithms.

It seems, then, that teaching physics should involve the progressive clarification of the relationship between mathematics and how we describe phenomena in physics. It should also involve an ongoing discussion of the nature of mathematics and the nature of science as well as the limitation of the mathematics used in describing physical phenomena.

The student must learn the correct way to manipulate symbols in algebra and trigonometry, and learn the nature of deductive proof in geometry. While this study is proceeding he/she should be making contact with the concrete world, but must come to understand fundamental concepts, such as speed, acceleration, mass, force, and energy, and how these are related, outside the grip of the *finished product* of explicit mathematical formulation, and, whenever possible, firmly placed in historical context.

Only when these concepts have matured in the mind of the student in the *pre-algorithmic* stage should one strive to arrive at the *finished product* of the symbolic and mathematical formulation of a concept. The self-confident dealing with the finished product of the mathematical formulation of a concept in physics then will lead to the knowledge of *precision*, and later to *generalization* (Whitehead, 1967) that guarantees deep understanding of "where the formulas come from".

**Galileo's Kinematics**

We shall examine the following hypotheses Galileo considered when selecting the appropriate one for the motion of a freely-falling heavy object.

1. Speed is proportional to distance covered.

2. One degree of speed is gained for each unit of distance fallen.

3. Accelerated motion is such that it adds an equal amount (increment) of distance in equal time.

4. Accelerated motion of free fall is such that speed increases with growth of time.

In our hypothesis - selection we are looking for the hypothesis (or hypotheses) that is (are) consistent with Galileo's Mean Value Theorem (see below), is expressible in Euclidean ratios, and consistent with the experimentally testable relationship between distance travelled and elapsed time. Here we have both *logical* and *empirical* constraints for the selection of a hypothesis, or hypotheses.

$H_1$ leads to a contradiction, as Galileo thought, by using a *reductio ad absurdum* argument. (See p. 168 of his *Dialogues Concerning Two New Sciences*.) It should be noted, however, that a *modern* mathematician would recognize that this hypothesis leads to a logarithmic function.

$H_2$ leads to the statement that units of distance=n degrees of speed, where n=1,2,3,...n. Thus 3 degrees of distance leads to 1+2+3, or 6 degrees of speed. This relation must be rejected because it cannot be expressed in terms of Euclidean ratios. In fact the relationship would lead to a logarithmic function, that Galileo would not have been able to deal with.

$H_3$ leads to the series 1, 1+d, 1+2d, 1+3d, ...1+ (n-1)d.

To calculate d: 1/(1+d)= (1+1+d)/(1+2d+1+3d) etc.

This is so because we have arbitrarily chosen a certain unit of time and therefore in the sequence of numbers representing spaces the ratio of the first number to the second number must be the same as the ratio of the first two numbers to the second two numbers, etc. Solving for d we obtain d=2.

We can now express the series of distances covered as 1+3+5+...n. But this series was well known to be equal to $n^2$. Therefore we can say that $1+3+5+...n= n^2$, or that Distance is proportional to the square of the elapsed time, or $d \sim t^2$.

Stillman Drake, for example, claims that Huygens used this

method to arrive at the "odd number rule" for uniformly accelerated motion. (See his "Galileo's Discovery of Free Fall," *Scientific American* 228 (May, 1973): 87.)

Finally, $H_4$ is correct because, in conjunction with the mean value theorem, it leads directly to the result that $d\sim t^2$. Thus, using modern algebraic notation, if $v_2 = a.t$, and $d= (v_2 +v_1 )/2 . t$, then $d= v_1 + (1/2)at^2$. Or, as Galileo wrote $d_2 / d_1 = (t_2 / t_1)^2$.

**The Mean Value Theorem**:

This theorem is found in Galileo's *Concerning Two New Sciences*, "Third Day", Theorem I, Proposition I:

The time in which any space is traversed by a body starting from rest and uniformly accelerated is equal to the time in which the same space would be traversed by the same body moving at a uniform speed whose value is the mean of the highest speed and the speed just before acceleration began.

Thus the mean (or average) speed of a freely-falling object, taken between speeds $v_1$ and $v_2$, is given by $(v_1 + v_2)/2$.

**The Contexts of Inquiry (outlined here for Newtonian physics)**

The *Context of Questions* refers to the claim that scientific fact is the answer to a scientific question. Scientific questions in turn are related to the basic assumptions of a science, often not explicitly articulated. We want to show students how these assumptions, often referred to as the presuppositions of a science, produce a small number of *foundation questions.* An example of a foundation question (for Newtonian physics) is: *What are the laws of motion that describe seemingly disparate phenomena such as free fall, the motion of a conical pendulum and elastic collision?*

Scientists, however, seldom refer to the foundation questions of a science, they consider them already answered. They only ask questions that relate to their research. These may be called *research questions.* An example of a research question is: *Does the electric force from a point charge decrease inversely as the square of the distance like the gravitational force?* This was a research question for Coulomb in about 1800.

Textbooks pose many questions in order to elucidate the laws, principles and definitions that a science like Newtonian physics is based on. These questions are *pedagogical questions*. An example of a pedagogical question is: *How is the second law of motion related to the first law?* The answers to the foundation questions shape the particular science. The research questions the physicist would ask, on the other hand, assist in working out the details of the application of the theory to appropriate phenomena. Textbooks, however, primarily deal with pedagogical questions and seldom directly discuss foundations questions and how these shaped a science, nor do they discuss research questions that the scientist may be interested in.

**The Context of Method** is concerned with showing the student that scientific method spans the whole spectrum from specifiable mechanical procedures to high-grade science that uses scientific imagination, intuitive thinking, and a sense what we may call aesthetic components. The "scientific method" as enshrined in textbooks generally stresses specifiable mechanical procedures only. We must, however, also acquaint the student with intuitive, non-mechanical procedures of the type used by Galileo, Newton and Einstein in developing their physics.

**The Context of Problems** involves the identification of the small set of problems that ultimately shaped a science. These are the *foundation problems* of a science. An example of a foundation problem in Newtonian physics is: *To find the nature of the path of a planet obeying an inverse square central force* *law*. Problems that physicists solve will be called *research problems*. Euler's solution of the problem of the spinning top in the eighteenth century is a good example of a research problem in Newtonian physics.

Such problems will be called *pedagogical problems*. Unfortunately, students often memorize their solutions in terms of algorithms, often without understanding the questions and contexts that generated them. An example of a pedagogical problem in physics is : *How far does a heavy object fall in 3.0 seconds, close to the surface of the earth*?

Textbooks generally concentrate on pedagogical problems only and seldom explicitly discuss the foundation problems of a science or the research problems of the practising physicist. When teaching is based on the contexts of inquiry, however, the foundation questions and problems would be discussed. Granted, when teachers and students in physics investigate a context like *Physics and the Bionic Man*, most of the questions and problems generated will resemble pedagogical ones. But many of the questions and problems will go beyond these and can be considered students' research questions and problems. These problems are those that do not fit into a known algorithmic procedure, do not have known answers, but can still be solved by the student using only elementary physics.

**The Context of Experiments** is first concerned with the foundation experiments, namely those that shaped a science. An example of a *foundation experiment* for Newtonian physics is Newton's experimental study of elastic collision using hardwood balls. Foundation experiments are seldom discussed in high school physics or chemistry classes. Textbooks generally fail to report them and teachers are seldom significantly acquainted with them. *Research experiments* are those designed by practising scientists (physicists, chemists, biologists). An example of a research experiment (for Newtonian physics) is Cavendish's famous experiment to find the numerical value of Newton's universal gravitational constant. Science teachers should also be concerned with the proper placing and classification of experimental work in science education.

Traditionally we involve the student in elementary physics or chemistry in the execution of *pedagogical experiments*. These are experiments that are conducted in a rigid step-by-step format that leads the student to an expected conclusion. These experiments seem to serve the purpose of "proving" or "verifying" such laws as Newton's second law of motion. First, it should be pointed out that it is not possible to "verify" a law by doing an experiment. Secondly, physics teachers must be honest with students and let them know that what they engage in when doing laboratory work is not a *bona fide* scientific experiment, i.e a research experiment. However, these activities can still be made more exciting and student-centered.

Going beyond type I experiments teachers should make provision for a number of other types of experiments. These experiments can be called *students' research experiments*. Type II experiments are those that are based on "real problems" (meaningful to the student), require simple apparatus that produce results seldom or never discussed in textbooks, are amenable to elementary physics or chemistry, but do not have obvious answers.

Type III experiments are small individual projects that have their origin in the imagination of the student. In physics, student might wish to build an accelerometer and test it in a car, or take stroboscopic picture of a baseball and study trajectory of a ball in the medium of air.

Finally, type IV experiments are essentially thought experiments of the type Galileo, Newton and Einstein "performed". Well-known examples of these are Galileo's thought experiment to show that all heavy objects on the surface of the earth must fall at the same rate, Newton's bucket experiment to clinch his argument for absolute space and time, and Einstein's elevator thought experiment to illustrate the equivalence of gravitational and accelerated frames of reference.

**The Context of History** is concerned with giving the student a good sense of how scientific theories are the product of historical setting and are paradigm-driven. In this context we could discuss confrontations in science and confrontations between the sciences and the humanities. Examples of the first would be the dispute between Newton and Huygens concerning the nature of light and the confrontation between Lavoisier and the phlogistonists in chemistry.

An example of the second would be the confrontation between Galileo's helio-centric solar system and the teachings of the Church which had adopted an Aristotelian geo-centric view of the solar system.

For each major topic the experienced science (physics, chemistry, biology) teacher can outline the contexts of inquiry. Science education students at the University of Manitoba have outlined this approach for major topics, such as light and optics, electricity and magnetism, and modern physics. They have also begun to design LCPs for chemistry and biology and applied the contexts of inquiry approach in these areas.

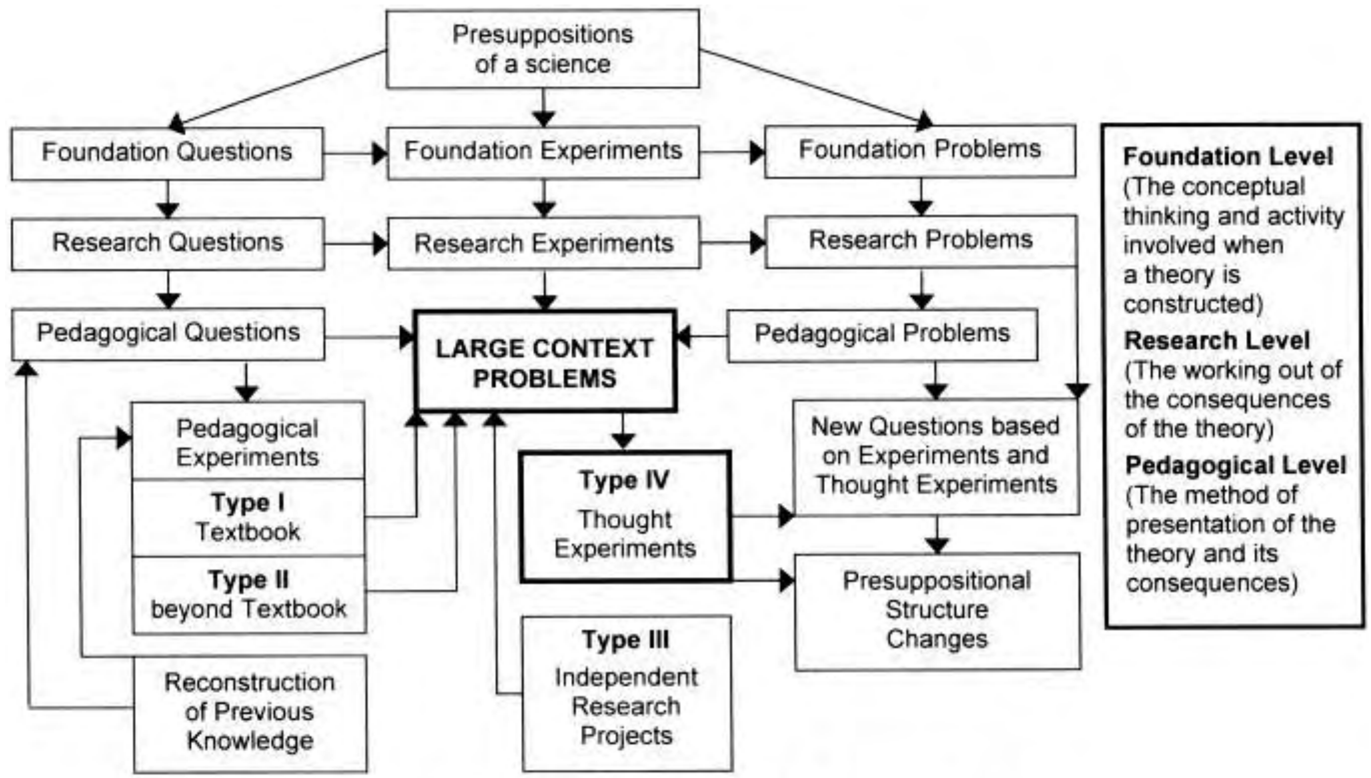


Figure 1: Levels of Investigation for Scientific Inquiry

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# Chapter 6

## Conceptual Development



The purpose of research in applied fields is to inform practice. In an ideal world the findings of university researchers in science education would guide the practice of teaching science. Unfortunately, we do not live in an ideal world and the teaching of science, more often than not, is based on a combination of educational folklore and teacher experience.

It is ironic that although science teachers know about science research they do not look more to research for guidance in their practice. But anyone who has taught school science knows that in the midst of a science lesson there is little time to reflect on research findings, much less on philosophical issues relating to science education. Under the pressures of classroom teaching, planning lessons for five or six different classes per day, some of which may not be in science at all, science teachers tend to be pragmatists, interested in what will work in their classroom tomorrow. Accordingly, if that ideal world in which research findings of university science educators inform the practice of science teachers is to be achieved, science educators must present their findings to the field in ways that encourage implementation by teachers.

A case in point is the simmering controversy within the constructivist camp between supporters of Piagetian theory and adherents to the alternative conceptual frameworks (ACF) viewpoint. Piagetian theory has been under attack for some years by supporters of the notion that firmly held ACF's derived from everyday experience impede science learning.

The constructivist perspective holds that we quite literally construct our own world from our personal experience, making sense out of new experience through the lens of our existing conceptual structures. Glaserfeld (1989) uses the term "transduction" to describe the processing of sensations into the conceptual structures that constitute one's personal knowledge. The constructivist paradigm contains two possible sources of difficulty in interpreting new experience. One based on a Piagetian theory points to inadequate mechanisms of "transduction"; the other based on an ACF theory points to already held ACF's derived from everyday experience getting in the way of acceptance of "correct" concepts.

**The Piagetian Perspective**

Piaget posits cognitive instruments which he terms operational schemata that the learner uses to make sense out of experience. Operational schemata are context independent and develop through a process of accommodation and assimilation. In Piagetian theory, cognitive development is the development of increasingly powerful operational schemata through these two processes. Garrison and Bentley (1990) bring the issue into philosophical focus by comparing Piaget's notion of assimilation to Kuhn's "normal science" and accommodation to his "revolutionary" science. This is a rather neat philosophical analogy but one which would do little to enlighten the "average" secondary science teacher, much less an elementary school teacher of science.

According to Piagetian theory, lack of understanding of experimental processes such as identifying and controlling variables and conceptualizations such as density and buoyancy result from poorly developed operational schemata. Hence Piaget's theory is concerned with process of transduction itself rather than the conceptual structures that result from transduction.

Typically, Piaget's concrete operational subjects were unable to apply a common explanation to a set of related phenomena in his clinical interviews. For example, after stating the principle of buoyancy, concrete operational subjects would use various explanations when explaining specific examples of objects sinking or floating. The following are excerpts from a Piagetian interview we videotaped some years ago of a Grade 11 student with a B average in chemistry on the topic of buoyancy.

**Interviewer**: You have placed these objects in the pile of floaters. Why will they float while these other objects will not?

**Subject**: These objects are more dense than water so they will sink but these others are less dense so they will float?

**Interviewer**: Alright, let's try them.

Some of the explanations for floating during the subsequent trials included "has air holes" "plastic floats, I don't know why", "it's made of wood and wood floats", and "the water is heavier" but could not elaborate. For sinking objects: "iron sinks", "no air holes", "the washer has a hole in the middle", "surface tension holds it up and it sank because you broke the pressure" and a variety of vague statements about air and water pressure.

It does not appear that preconceptions interfered with comprehension. Rather, the subject was unable to apply a consistent explanation to the various examples and saw no need to do so. While Piaget was loathe to suggest interventions to promote cognitive development in such cases a reasonable approach seems to be to provide unspecified learning experiences requiring lots of accommodation and assimilation.

**The ACF Perspective**

Linn (1982) criticizes Piaget's theory as under-valuing the role of prior knowledge in understanding science and focusing excessively on content-free strategies. She cites a plethora of studies, many her own, supporting the importance of factual knowledge in reasoning. These studies are strengthened by common-sense and the experience of high school teachers across North America. It would, indeed, be difficult for a high school chemistry student to reason logically about stoichiometry without a pretty thorough understanding of the mole concept. On the other hand, even an inexperienced cook with a moderate ability to reason about proportionality could scale down (or up) a recipe for corn bread. Clearly, the former case requires a significant amount of domain-specific knowledge while the latter requires little more than a reasonably well-developed operational schemata for proportional reasoning. A common stratagem used by chemistry teachers when teaching stoichiometry is to teach first for understanding. However, this means decontextualizing problem solving, then, when that fails (as it inevitably does with some students) to teach algorithms for standard problems to enable the student to pass the next examination.

Garrison and Bentley (1990), support the ACF position on philosophical grounds. Drawing an analogy between an ACF and a current science paradigm they suggest that students have difficulty accepting new conceptualizations in the face of a firmly embedded set of highly verified conceptualizations derived from everyday concrete experience. The ACF prescription would be to challenge these ACF's in various ways.

**The Classroom Teacher's Perspective**

What is a science teacher to do when confronted by complex arguments and seemingly contradictory theories put forth by learned researchers? Clearly, if research is to have any influence on practice, it must be presented to the science teacher in a form that is meaningful and usable.

Large context problems (LCP's) as proposed by one of us (Stinner) are an instructional strategy that addresses both points of view. Appropriately designed LCP's are inherently more interesting than the contrived problem exercises found in most text books. They require the learner to integrate knowledge and ideas from a variety of sources and LCP's can be worked on in groups. The latter is of great benefit because cognitive conflict resulting from the social interaction among peers is much less threatening than when created by interaction with a teacher. A further advantage of LCP's is that they do not readily yield to the application of algorithms.

**The large context problem**

The LCP approach was originally developed as a response to the discovery that *learning could be well motivated by a context with one unifying central idea capable of capturing the imagination of the student* (Stinner, 1980, 1981, 1989). For each given major topic in physics , such as kinematics, several LCP's for the teaching of high school physics were developed. The student then chooses <u>one</u> LCP that attracts him/her. However, each LCP had to be so designed that *all* of the physics for a particular topic is used for the successful completion of the problems suggested by the context. What is so attractive about this kind of setting is that the problems are generated <u>naturally</u> by the context and will *include* problems that are artificially given <u>out of context</u> in a textbook for a given topic. Moreover, students' responses to the LCP approach suggest that they should be designed by the instructor. Indeed, ideally, LCP's should be designed cooperatively by students <u>and</u> the instructor. This also gives the instructor the status of researcher and the student the feeling of participation in an on-going research program.

Teachers, of course, have used such approaches in the past. The design of simple mechanical contrivances to perform some task would be one kind of large context problem. Tinker toys or erector sets are an excellent medium for doing large context problems. The *mechano sets* of the post-war period and *legos* used by today's children are well suited for creating LCP's for a children. These settings then become the student's first significant and organized "hooking on to an aspect of the world of his/her choosing" (Stinner, 1989), in what Whitehead (1967) calls the *stage of romance*. This stage provides the setting for problem solving, or what Whitehead calls the *stage of precision.*

The LCP approach requires the learner to integrate knowledge and ideas from a variety of sources. One of the principles that should guide us in designing LCP's is that "cognitive strategies will be most effectively developed if students are exposed to a variety of novel problems...in contexts which are as close to eventual transfer situations as possible...(Allen and Whyte, 1980). di Sessa (1988) and Driver (1989) argue that children do not have organized theories about the world, but possess a large number of fragments. Transition to scientific theories then involves the systematic organization of these fragments. Driver recommends that provision be made for students to receive a "range of experiences within a domain and to support and encourage the systematic and coherent organization of students' interpretation of those experiences" (Driver, 1989).

We have found that students regard appropriately designed LCP's more interesting and motivating than the contrived problem exercises found in most text books.

Our experience suggests that the immediate benefit of contextual problem solving (carried out concurrently with, or right after, conventional classroom teaching) is that it enlarges the student's understanding of basic laws and principles. In addition, the student often goes beyond just the successful mastery of the problem situations. For example, for the study of kinematics, if the student chose, say "Physics and the Bionic Man", he/she investigated the current research in the physics of bionic parts; or if the student chose "Physics on the Moon", he/she investigated the physics of moon architecture and the general problem of adaptation to low-gravity environment (Stinner, 1989). In this manner the LCP approach provides a vehicle for traversing what Whitehead (1967) refers to "the path from romance to precision to generalization".

**Historical setting as a vehicle for conceptual change**

There is a growing sense among many researchers in science education that one sees "tantalizing parallels between intuitive conceptions in certain domains, e.g., mechanics electricity, astronomy, and historical prescientific conceptions" (Nercessian, 1989). Granted, we cannot expect students to recapitulate high-grade scientific thinking of the Aristotelian or the Galilean variety. However, we can make a plausible case for an essential recapitulation for domains that are familiar to the student. Driver and Easley, reported that students' views often "reflect analogies with historically held views" (Driver and Easley, 1978).

Many researches claim that students have "Aristotelian" ideas about the relationship between force and motion, and demonstrate "medieval" understanding of motion that is akin to the concept of impetus (di Sessa, 1982, Viennot, 1979, Driver, 1985, p. 88). Even in areas that are further removed from everyday experiences, such as electricity, researchers claim that students seem to have an intuitive understanding of *electric fluid*, not unlike that held by the *electricians* of the late 18th century (Shipstone, 1989). Of course, students do not have Aristotle's clear understanding of the difference between *violent* and *natural* forces (what we today call contact forces and action-at-a-distance forces). Nor do students have a notion of *impetus* that even resembles the complexity of the concept in the context of medieval physics.

It follows then that students are unlikely to have private theories that suggest an understanding of *inertia*, for example, as first realized by Galileo and later propounded by Newton. Nor do they show ideas that would lead them to the charge theory of electricity, as propounded by physicists in the first half of the nineteenth century. It seems that students preconceptions, which are based on everyday experiences, do not prepare them for such abstract and refined concepts as *inertia* or *electric charge.* There is little doubt that learners actively construct ideas about phenomena around them. However, " this does not necessarily indicate that a learner has, for example, any kind of theory of 'naturalistic' physics" (Kenealy, 1989, p. 210.).

Driver makes a similar point quite strongly:

> Learning science, therefore, is seen to involve more than the individual making sense of his or her personal experiences but also being initiated into the "ways of seeing " which have been established and found to be fruitful by the scientific community.
>
> Such 'ways of seeing' cannot be 'discovered' by the learner - and if a learner happens upon the consensual viewpoint of the scientific community he or she would be unaware of the status of the idea" (Driver, 1989).

According to Garrison and Bentley (1989) neither the ACF advocates of domain-specific theories nor Piagetian global theories of developmental psychology entirely account for the difficulties students have in accommodating high-level concepts such as *inertia*. What seems to be involved in the accommodation of a concept like Newtonian concept of *inertia* is a complete "breaking with everyday experience" (Garrison and Bentley, 1989).

Duschl and Hamilton (1990) investigate the consequences of the assumption that the "process of theory development by scientists can be compared to an individual's acquisition of knowledge of the world". Their concern seems to be the need for a clear differentiation between the contexts of justification and the context discovery. They argue that a problem arises when a choice must be made between presenting a theory in a classroom in the *historical context of justification* mode or in the *historical context of discovery* mode. The distinction between these two contexts would suggest that we use the first whenever we talk about *normal science* and the second whenever we talk about *revolutionary science*. This usage would then correspond respectively to *weak restructuring*, or what Piaget calls *assimilation,* and to *radical restructuring,* or what Piaget call *accommodation.* However, we make the initial assumption that in most historically-based science stories we will develop, *radical restructuring,* or *accommodation* on the part of the student will take place. We wish to argue that this kind of *conversion*, or *Gestalt switch* can best be accomplished by contextual teaching in a historical setting.

Another good reason for teaching science in historical context is given by Novak. He argues that the meaning of a concept is strengthened and defined by the "network of propositions the learner has connected to it" (Novak, 1977). In this statement we interpret Novak to say that concepts, such as *electron*, for example, are fully understood only if in the mind of the learner the concept is diversely connected (electricity, chemistry, atomic theory, *etc.*). Our hypothesis is that *diverse connections that enrich conceptualization can effectively be established in a multidisciplinary context that attracts the student* and *is historically well placed*. This latter claim can be regarded as the criterion whereby we would differentiate between *bona fide* concepts and theories in science, and 'children's theories', "having a coherent internal structure and being used consistently in different contexts" (Driver, 1989).

Finally, both the ACF advocates and Piagetians recognize the value of studying case histories in science. These historical studies are thought to provide new insight for science educators about concept formation. We will discuss the requirements of the historically placed science story, after briefly summarizing attempts to introduce a "story-line" to science teaching in general.

**The "story-line" approach to the teaching of science**

As early as 1947 J.B. Conant introduced his *Understanding Science: An Historical Approach,* followed by the splendid series (and still fresh) *Harvard Case Histories* (Conant, 1957). At about the same time Gerald Holton made a credible attempt to integrate the history of science in his otherwise conventional treatment of university undergraduate physics in his *Foundations of Modern Physical*

*Science* (1957). These historical approaches have been and continue to be successful in the hands of a few teachers who see relevance in imparting historical knowledge to students (Arons, 1988). Even the writers of the highly academic *PSSC Physics* series attempted to thread the theme of *particle-wave* duality of nature as a "story line", however contrived, throughout the presentation. A few years later the *Harvard Project Physics* series (1967), under the leadership of Gerald Holton and Fletcher Watson, introduced a history-based textbook series. This series also uses "story-lines" based on such themes as wave-matter duality, entropy, and mass-energy equivalence, and on controversies such as those between Leibnitz and Descartes, Newton and Huygens, and Copernicus and Ptolemy. This series was, by consensus, a "glorious failure" to replace the conventional physics texts. Many physics instructors, however, still use these books as their most trusted reference for historical context and ideas for imaginative teaching.

Several writers and science education researchers have recently again recommended and have elaborated the notion of using a "story line" approach to the teaching of science. Arons (1989) believes the best way to attract students' attention as well as organize a science course is by way of a "story line". He outlines in some detail the historical settings of important discoveries and events. Arons is referring to what are essentially good science stories that have intrinsic interest and show connections not to be found in textbooks. These stories seem to be excellent small versions of Conant's case histories "that can be infused into introductory courses, without seriously affecting the amount of physics being covered" (Arons, 1989).

Michael Ruse has designed a large-scale case study based on the controversy between creationism and the theory of evolution. He uses this study to set a large context with *one unifying central idea that attracts the imagination of students*. He says: "rather than simply going straight at students with such worthy (but boring) standard topics as criteria of confirmation, conditions for adequate explanation, and the like- at least, rather than going at students abstract isolation- one does better to plunge into actual areas of science, from which the pertinent philosophical messages can be extracted" (Ruse, 1989). In other words, he set a LCP that *generates the major ideas and problems of the philosophy of science naturally*. The last requirement of a well-placed LCP, namely that the context be designed by the instructor, was also fulfilled.

Jutta Luhl, a German science teacher, has developed a "story-line" approach to teach atomic theory in Middle Schools. Rather than "teach the Bohr model of the atom at a very mechanical level", she has developed a mini-course that traces the development of the idea of *atom* from the Ionians to Dalton (Luhl, 1990). Like Ruse, Luhl set a large context in which one central idea that attracts the imagination of the student the important connections that lead up to the Bohr atom are explored. These include an understanding of the historical evolution of the idea of the *atom*, including basic principles, such as the conservation of mass and energy and the law of definite proportions. This approach may be more time-consuming then the conventional textbook approach. However, the understanding of the student as well as the quality of interaction between the student and the teacher is lifted from an ordinary to a high-grade level.

Recently Kieren Egan has argued against the dominant objectives-based procedures of curriculum planning and recommended a procedure based on the story form. His argument is that the story metaphor is more appropriate in describing what we learn about the world, according to research based on "constructivist nature of human sense making" (Egan, 1986).

Wandersee has been using Egan's *Story Form* in developing what he calls *Historical Vignettes* to enhance the teaching of science to young students. He uses "carefully chosen examples from the history of science...tailored to the interests of the science students..,"(Wandersee, 1990). We will use some of Egan's ideas of planning a story in *general* for designing "science stories" in historical contexts.

In seems that all of these writers to a lesser or greater extent recommend a "story-line" organization of a science topic that resembles our original LCP approach. In summary, the central features are based on the following recommendations:

1. Map out a context with one unifying central idea that is deemed important in science and is likely to capture the imagination of the child.

2. Provide the child with experiences that can be related to his/her everyday world as well as being simply and effectively explained by scientists' science, but *at a level that "makes sense" to the student*. (If ideas and concepts are introduced too early, the child may not be intellectually ready; if introduced too late the child's science may be ossified into layman's science: the child will, have lost interest (Osborne *et al*, 1983)).

3. Invent a "story line" that will dramatize and highlight the main idea. Even though the main idea or ideas are should be placed correctly in history the story may or may not be historically correct (remember *Galileo and the Leaning Tower of Pisa* story!) Egan's recommendation that one should

*identify an important event associated with a person and find binary opposites, or conflicting characters or events* may be appropriate here.

4. Ensure that the major ideas, concepts and problems of the topic are generated by the context *naturally;* that it will include those the student would learn piece-meal in a conventional textbook approach.

5. Secure the path from *romance-precision- generalization.* This is best accomplished by showing the student that

a. problem situations come out of the context and are intrinsically interesting,

b. that concepts are *diversely connected*, within the setting of the story *as well as* with present-day science and technology.

c. there is room for individual extension and generalization of ideas, problems and conclusions.

6. Ideally, the science story should be designed by the instructor, ideally in cooperation with students, where he/she assumes the role of the *research-leader* and the student becomes part of an on-going research program.

These six features then will comprise our revised LCP, that we now call "science story". Telling a coherent story, with a beginning, a middle, and a provisional end, may be the best way for learning, remembering and re-telling of ideas (Kenealy, !989, Miller, 1988). Kenealy reminds us that "In fact, most people will impose coherence on a set of random sentences in an attempt to create a context for what they are reading or hearing (Kenealy, 1989).

Our ultimate aim should be to introduce children to science, much the same way as they have been "inducted into full membership of their culture" (Egan, 1988). We would like to take up the challenge contained in the plausible suggestion "that the role of the story or the shaping narrative is becoming increasingly recognized in all subject areas, *even in the sciences,* which had once seen themselves as positivistically immune from subjective shaping" (Egan, 1988).

The following is a brief summary of a course that we introduced at the university of Manitoba. In this program we attempt to teach student-teachers the craft of designing a "story-line" which is oriented toward elementary and junior high school science teaching. We will now turn to discuss briefly the content and pedagogy of teaching this craft to fledgling science teachers.

**Write your own science story: Teaching the history of science to student teachers**

We are offering a course (senior elective) at the university of Manitoba that looks at the development of science education in terms of the major achievements of science as well as the practices of scientists throughout history. From these achievements and practices students are asked to draw materials to develop hands-on teaching contexts, namely "science stories". These must be designed according to our discussion above, to be used in the elementary or junior high school science classroom. The science stories are then presented to class for a critical examination (essentially a *peer review*). Students design four "science stories", one for each of the major historical epochs (see below). These "science stories" are now being edited and will be used in the class room.

I. **The Ionians, and the Greeks (From Thales to Ptolemy).**

The science of the Greeks, because it is essentially high-grade thinking based on unaided observation, seems especially well suited for teaching elementary school and junior high school science.

In fact, one can argue that the "teachable moment" of the historical context in science is precisely at this time (10-14 years) and perhaps again in graduate school. It may be critical at what age we introduce experiments and ideas in science. If we introduce them too early we will encounter problems because intellectually students are not ready. If we introduce them too late "children's science can ossify into layman's science,...showing little or no motivation to change their present view (Osborne *et al*). Science teachers in high school know that it is very difficult to teach science in historical context because students, as Kuhn has pointed out, "know what all the answers are" (Kuhn, 1962). (see feature No 2. above)

Archimedes' law of the levers, his law of flotation and his law of reflection involve elementary science concepts that are best taught in historical context.

The following are examples of topics related to the science of the Ionians and the Greeks that can be developed into teaching units based on "science stories":

-The three *laws of physics* (reputedly discovered by Archimedes) that have essentially remained unchanged: law of the lever, law of flotation, and the law of reflection.

-Archimedes' mathematics, as it applied to his physics. Archimedes' screw, and Archimedes: physics and war machines.

-Determination of the length of the year and the circumference of the earth: Aristarchus, Eratosthenes.

-Plato's cosmological question: "By the assumption of what uniform and ordered motions can the apparent motions of the planets be accounted for?

_Plato's theories about the origin of the universe

-Zeno's paradoxes.

-The experiments of Empedocles; for example, "the water clock experiment", his experiments in optics to test his theories.

-Democritus' atomic theory of matter.

-The three outstanding mathematical problems of the Greeks: the squaring of the circle, the trisecting the angle, and the *Delian* problem.

-Hippocrates and medical science.

-Aristotle's biological studies, his physics and his great experiment: "The embryology of the chick".

-The Ptolemaic solar system.

-Hero's experiments.

2. **Later Middle Ages to Copernicus**

Young science students are especially well predisposed to consider some of the main scientific concepts as put forth by the natural philosophers of the middle ages. The notions of *impetus* and *mean value* in physics and the application of a simple atomic theory in chemistry are examples of concepts that lend themselves to profitable classroom discussion.

The following are examples of topics related to the science of the middle ages that can be developed into teaching units, based on "science stories":

- The concept of *impetus* in the teaching of motion.

- The application of the *mean value theorem* to problems involving average value.

-The optical experiments of Theodoric of Freibourg, especially the experiment to discover the "Causes of the Rainbow".

- "A day in the life of an alchemist."

- Roger Bacon's philosophy of scientific method.

- Medieval optics and theory of light

- Could medieval physicists have developed a telescope?

- Roger Bacon (13th century), the "new scientific attitude" and the nature of scientific enquiry.

- Thomas Aquinus' attempt to reconcile the scriptures with the physics of Aristotle.

-Robert Grosseteste and scientific enquiry. His discussion of the inductive process deals with the passage from observation to laws anticipates the 17th century scientists' understanding of scientific method.

-Nicolas Oresme anticipated much of Galileo' work on motion.

**3. From Copernicus to Newton: The Scientific Revolution.**

Most of the scientific developments and concepts of the Renaissance (Copernicus' geocentric model of planetary motion, Harvey's circulation of the blood) as well as those of the scientific revolution proper ( Galileo's inclined plane and pendulum experiments, Torricelli's measurements of barometric pressure, Boyle's experiment, Hooke's law) are teachable to young students (10-14 years).

The following are examples of topics related to the science of the Renaissance and the seventeenth century that can be developed into teaching units, namely "science stories":

-Copernicus and the geocentric solar system.

-The problem of navigation in the 15th and 16th centuries.

-The Julien calendar: why reform was necessary.

-The problem of finding the longitude at sea.

-Observations of the sky for children.

-The compass and how it changed navigation.

-Mercator and the problem of representing the spherical earth upon a plane map for the purpose of navigation.

-The development of the theodolite and triangulation for determining distances.

-Leonardo da Vinci's mechanical inventions.

-Vesalius and the study of anatomy and physiology.

-Chemistry in the 15th and 16th centuries.

-Galileo's inclined plane experiment.

-Galileo' telescope.

-Robert Hooke and the microscope.

-A day in the life of Robert Hook, FRS.

- Galileo' astronomical observations.

-Newton's mechanical experiments.

-Newton's optical experiments.

-Harvey's theory of the circulation of the blood.

-Roemer's determination of the speed of light.

-Kepler's "War on Mars".

**4. From Newton to Einstein: The Modern Period.**

Many of the main ideas and concepts in biology, chemistry and physics of the 18th and the first half of the 19th century can be discussed in early science education and many of the key experiments replicated. The story of Lavoisier and the chemical revolution and Dalton atomic theory is appropriate for elementary and junior high school science. Faraday's electromagnetic experiments are easily performed using simple materials. In biology teachers should develop simplified approaches to show how Pasteur's experiments refuted spontaneous generation and how Semmelweiss' observation led to the germ-theory of disease. Most of the experiments involved in Faraday's work on electricity and those in Joule's work in establishing the principle of the conservation of energy are easily replicated and the relevant concepts amenable to elementary analysis. We should probably do better here than what conventional textbooks would allow us to achieve.

Pasteur's method of "disproving" spontaneous generation is still considered the textbook case of controlled experimentation in biology. Moreover, his experiments that laid the foundations of the germ theory of disease can be understood and replicated by young students. Textbooks in general miss the opportunity to create the appropriate excitement in showing how to replicate them.

The following are examples of topics related to the science of the 18th and the 19th centuries, that can be developed into teaching units based on "science stories".

-The *phlogiston theory* in chemistry.

-The confrontation between Priestly and Lavoisier over oxygen.

-Lavoisier's experiments to investigate oxygen.

-Volta's experiments with electric batteries.

-Dalton's assumptions, his observations and his experiments which led to his atomic theory of matter.

-Davy's experiment separating water by an electric current.

-Chemical shorthand: from the alchemists to Dalton and then to Berzelius

-Faraday's electromagnetic experiments.

-Young's experiments to demonstrate the wave nature of light.

-Making a simple spectroscope.

-Determining the distance between two point by triangulation.

-Determining the distance to a star by the parallax method.

-An account and a discussion of Darwin's *The Voyage of the Beagle* as a background to his theory of evolution.

-A discussion and partial replication of Pasteur's experiments to put to rest *spontaneous generation*.

-The evidence for the germ-theory of disease.

-The story of the unit charge in electric phenomena: from Coulomb's measurements, to Faraday's electrochemical experiment

to Thompson's discovery of the electron. Do electrons really exist?

-John Tyndall and the *Tyndall Effect*.

-Faraday's lecture on "A Burning Candle".

-Laplace' theory of the origin of the universe.

-Linnaeus' classification: an improvement over Aristotle's?

-The Doppler effect and its use in astronomy.

-The discovery of Neptune: Newton again vindicated.

-Chemistry, Physics and the discovery of photography.

Our aim is to extend this program and reach into the 20. century. We want to set up contemporary contexts that make connections with the past by way of those "science stories" that the student is already acquainted with.

**Summary and Conclusion**

ACF researchers interpret their findings to mean that students are reluctant to give up their views about the world because of the utility such views provide. These researchers argue that conventional formal (expository) instruction is unlikely to permanently change students' views. In fact, pre-scientific views seem to persist even after students receive good marks on putative problem solving tests. This strongly suggests that students are being taught concepts primarily by way of algorithm-recitation techniques.

On the other hand, a Piagetian interpretation of the same data implies deficiencies in the development of students' cognitive structures. A Piagetian prescription would be to challenge the student with experiences that create disequilibration that requires accommodation and assimilation. The aim of these experiences would be to produce cognitive development.

We argued that even if the clarification of the epistemology of concept formation in science were possible it alone would not provide us with clear implications for the teaching of concepts. However, AFC advocates as well as Piageans, would agree that understanding in science requires non-mechanical approaches that appeal to the imagination and involve such procedures as analogy, limiting case analysis, thought experiments, and especially on-going discussion.

Conceptual change, of course, has always been a learning process for the scientist as well. While it is manifestly clear that we cannot expect the learning process to simply recapitulate the historical process, we believe that we should be able to foster a good understanding of history and in a limited sense (as in the case of elementary kinematics and dynamics) recapitulate the historical development.

Therefore, we have argued, a sound understanding of science must include historical context. The contexts of discovery and justification must be given in order to provide appropriate evidence of true comprehension of science, both as a process and as a product.

To teach science in a historical context we require teachers who have more than a cursory acquaintance with science history and who know the basic findings of the philosophy of science. In addition, we maintained, science teachers will be more effective if they teach by way of *science stories* (large context problems) that are connected to the history of science and provide appropriate evidence for the formation of concepts. In order to do that, we stressed that science teachers must be able to develop their own *science stories* and show facility in using them in a classroom. Moreover, we have described how we developed a course for senior students in science education that surveys the development of the major scientific ideas from the Ionian physicists to the present. One of the tasks in this course is for science education students to develop *science stories* for the main scientific epochs. These are then presented in workshop format, extensively discussed and criticized by other student teachers. Ultimately these *science stories* will be used in the classroom to provide appropriate evidence toward conceptualization that appears to the student to be intelligible, plausible and fruitful.

We are claiming that the instructional strategy of contextual teaching by way of "science stories" addresses both the ACF and the Piagetian points of view. Moreover, it appears that historically-based science stories might be one important way to bring about accommodation, or radical restructuring. This seems reasonable because the context of discovery is stressed naturally when developing science stories. We are looking for further testing, in actual classroom application, of our original hypothesis that *diverse connections that enrich conceptualization can effectively be established in a multidisciplinary context that attracts the student and is historically well placed.*

Ultimately one would like to see a two to three year program (10-14 years of age) that guides the student through historical contexts starting from the Ionians to the present. The science stories should be grouped in such a way that no matter which one the student picks from a given cluster, the content and processes covered will match those in the prescribed curriculum. However, practicality may demand placing the students into manageable groups of 3 to 4, while working on 3 to 4 different science stories.

Let us take, for example, the three laws of physics that the Greeks discovered (see above). To attract the interest of all students, one could easily develop quite different settings and dramatizations (this was successfully done by the student teachers). Teachers then could capitalize on having students discuss these contexts both formally and informally, thus offering different points of view. Problems which arise naturally from the contexts then can be presented by the students. The diversity offered by the different story-settings would then enrich the students' background knowledge as well as stir further interest.

Ultimately one can envisage science being taught by way of historically based contexts from elementary grades right up to high school. In an ideal world, contextual teaching based on a "story line" could go on until specialization would seem to be inevitable. In such a world, textbooks would have to be rewritten and their role reconsidered.

In the real world, however, textbook-centered teaching appears to serve mainly those well who are already committed to science, namely our future "normal scientists" (Aufshnaiter, 1989). It seems plausible that textbook science discriminates against the highly gifted as well as the student in search of general scientific understanding (von Baeyer, 1990). As Kuhn (1962) pointed out, textbook science alone is unlikely to produce the scientist "who will easily discover a fresh approach", or, we may add, educate the layperson who will be scientifically literate. To achieve such a goal, science teachers must recognize the motivating potential as well as the pedagogic superiority of science stories, appropriately placed in historical context.

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# Chapter 7

## Science Textbooks: Their Present Role and Future Form

Present evaluation of science textbooks

William Whewell and the first physics textbooks

Science teaching and science textbooks

Textbook-centered teaching and normal science

A pedagogical dilemma

Science textbooks and the LEP model of conceptual change

Science textbooks, present problems, and their future form Implication for science education

The research on textbook quality indicated that there is little good to say about an instructional tool that is relied on so heavily. There was little text devoted to science, technology, and society issues; scientific literacy; inquiry; and concepts were not placed in historical context. Elementary texts required reasoning beyond the capabilities of the students.

...It strikes me that looking for ways to improve a method of instruction that has been consistently proven to be less successful than other methods is a strange activity for science educators. ...responsible science educators should not capitulate to poor practice because it is the reality. They should continue to argue for good practice and conduct research that makes the implementation of that practice easier for teachers (Baker, 1991, p. 367).

Baker (1991) made the above observations following a summary of research on textbooks in the journal *Science Education*. Baker's observations are consistent with a widely held view that in science teaching the textbook plays a dominant role and dictates both what is taught in science and how it is taught (Shymansky and Kyle, 1992; Yager, 1983, 1992; Yore, 1989, Wheatley, 1991). Ten years ago Yager (1983) summarized research on science textbooks. His conclusions seem to be, to a large extent, as valid today as they were then. He stated that the most significant decision science teachers make is the choice of a textbook. Yager argued that textbooks imprison science teachers in a belief that the instructional sequence of assign, recite, and test is guaranteed to produce knowledge. He went on to emphasize that direct experience is almost never offered, and laboratory work, if it occurs at all, is of the deductive-verification type. He claimed that high reliance on textbooks does not seem to produce scientifically and technologically literate graduates. Yager concluded cryptically that "The status of science education can be summarized in a single word: textbooks" (Yager, 1983, p. 578).

One of the serious shortcomings of most textbooks seems to be that they implicitly or explicitly promote the empiricist-inductivist picture of science, namely, the belief that laws and discoveries are a guaranteed consequence of systematic observation that is based on a specifiable scientific method (Hodson, 1987; Shelley, 1989; Stinner, 1989; Yager, 1983). Another shortcoming of many textbooks is the implication that a clearly presented lesson that is based on the instructional mode of lecture, question and answer, is guaranteed to produce knowledge. Moreover, textbooks in general are content-driven. Chiapetta, Sethna, and Fillman (1991) examined chemistry textbooks and found that "all of the chemistry textbooks deemphasize science as a way of thinking" (page 949). They argue that if content coverage drives chemistry courses students will not become scientifically literate in the broad sense which was recommended in the position statement by the National Science Teachers Association (1982).

Historians and philosophers of science, however, tell us that scientific concepts and theories do not follow from observation in a simple inductivist manner and that scientists in fact study a world of which they are a part, and not a world from which they are apart. This picture of science requires that students learn to look at scientific data with their ideas that are based on their personal experience and understanding. At the same time cognitive scientists tell us that knowledge is actively constructed by the child and not passively received from the environment (Driver, 1989; Hewson & Thorley, 1989).

Learning is now generally seen as an adaptive process in which the learner's conceptual schemes are progressively reconstructed in keeping with a wider range of experiences (Driver, 1989).

A discernible shift is now taking place in how science educators and science teachers view the relevance of recent findings in the history and philosophy of science (Arons, 1989; Jordan, 1989; Rohrlich, 1988, Stinner, 1992). An equally important shift is occurring in how science educators view the nature of the learning process (Kyle, 1991; O'Loughlin, 1992). There is even evidence that these important findings and views are becoming known to classroom science teachers and textbook authors.

Why have such important findings and arguments about the nature of science and the nature of the learner not made a greater impact on science textbook authors and on science teachers? In trying to answer this question, Kyle and Shymansky (1991) remind us "most science education research produces knowledge in the context of a system clinging to tradition" (p. 756). One important aspect of this tradition is connected to the prevalent use of textbooks.

Textbook-centered science teaching culture rests on two presuppositions: that there is a specifiable scientific method that guarantees success, and that the expert is able to break down the content into teachable units that can be sequenced for the consumption of the learners. The learners therefore are indoctrinated into an unsceptical acceptance of an inductivist-empiricist picture of science. Moreover, learning is seen as a slow accumulation of knowledge through practice, where the learner is assumed to be, in the John Locke tradition, a *tabula rasa*. (Wheatley, 1991). Science teachers learn their science from textbooks and obtain their early teaching practices in textbook-oriented classrooms. They then teach from textbooks that largely emphasize memorization of scientific facts in an ongoing rhetoric of information.

This article will examine two parallel views, namely those of Thomas Kuhn and William Whewell, of the role of science textbooks. Kuhn's insightful and influential comments about the role of the textbook in science education will be compared with William Whewell's ideas about good pedagogy in physics education. Thomas Kuhn is a leading contemporary historian and philosopher of science while William Whewell was the premier British philosopher of science of the nineteenth century who wrote the first important physics textbooks. Both are deeply concerned about how students learn concepts in science education and both have a great deal to say about the relationship between what may be called the *logical plane of activity* and the *evidential plane of activity* of science. It is argued that good science teaching not only has to pay more attention to how these planes are related but also must recognize and respect the third plane of activity, namely the *psychological plane of activity.* Later, a conceptual model (Stinner, 1992) that relates these three planes of activity will be presented (Fig. 1). Many researchers have found that sound understanding of science concepts can generally not be developed from textbook use alone (Baker, 1991; Loewenberg-Ball & Feiman-Nemser, 1988; Renner, Grybowski, & Marek, 1990). In the following sections I will expand on the foregoing and will conclude with some plausible recommendations for improving the future form of science textbooks.

## WILLIAM WHEWELL AND THE FIRST PHYSICS TEXTBOOKS

The first widely-used textbooks in elementary physics in the English-speaking world were written by William Whewell. In the preface of his *An Elementary Treatise of Dynamics (* first published in 1823), he especially complimented the continental mathematicians for their analytical skills " in compressing the whole science into a few short formulae" (Whewell, 1850, p. 41). In spite of this tribute Whewell was deeply concerned about the seductive powers of the finished product of mathematics in the teaching of physics. He argued that students should learn concepts outside the grip of a mathematical formulation. He thought that if they did not struggle through appropriate arguments based on intuition, space, and geometry first they would only "learn to reason by means of symbols...; and by means of the general rules of combining and operating upon such symbols; without thinking of anything but these rules". (Whewell, 1850, p. 41).

Whewell put his pedagogical principle into practice of placing intuition, geometric reasoning and pre-algorithm discussion *before* the finished product of mathematical formulation. While it is arguable that textbooks in physics that followed were modeled after his, many of Whewell's pedagogic devices to explicate concepts *prior* to the presentation of the finished product were dropped. In these later text books (see, for example, *Natural Philosophy* by John Sangster, 1864), authors first stated the principles, definitions, and laws and then, sequencing the problems, asked students to work them out as an exercise.

In contrast to Whewell's treatment, extensive discussion of the origin of and the evidential basis for mathematical formulations was discontinued. In these texts example problems are worked out to illustrate the application of formulas. It seems that "post-Whewellian" texts are the prototypes for today's physics texts, and they may have set the tone for the format of science texts in general.

## SCIENCE TEACHING AND SCIENCE TEXTBOOKS

The teaching of science in general and of physics in particular has been a textbook-centered affair in the English-speaking world since Whewell's textbooks appeared in the 1820s. To be sure, we have made some progress since then. Most modern textbooks attempt to provide the student with a link between what is considered an established scientific fact of a topic and the concrete level of evidential and experiential support given to it. However, science textbook writers as well as science teachers seem to emphasize the finished product of scientific fact and mathematical formulation in the teaching of physical science. Students, in turn, are trapped by the efficiency of memorizing the scientific fact and the efficacy of applying the formulas in solving exercise problems. The correct solution of the exercise problems then provides evidence for the teacher of the teaching effectiveness and it gives the student a sense of confirmation of mastery and understanding of the material (von Baeyer 1990; Hewitt, 1990; Stinner, 1992).

This overemphasis of the mathematical formulation of a topic at the expense of the appropriate *evidence* to support it is apparent in the study of the physical sciences, especially in elementary physics. Former science (physics) students will no doubt remember in particular solving countless problems by using formulas based on laws, principles and definitions, and performing experiments to verify these laws. Newton's second law, for example, has been proved by generations of students, whether this proof involved the use of *Atwood's Machine*, *Fletcher's Trolley,* or the use of the electronic air table. Newton's first law, the textbook may have told us, is just a special case of the second law. But does that follow deductively? Can we perform experiments to "prove" the first law? Did Newton use inductive reasoning in arriving at these laws? If so, how is it that his laws are used as one would use a deductive system in geometry, as Whewell, among others, insisted could be done?

The historically oriented Harvard Project Physics series does consider such questions, but most textbooks seldom do. If they occasionally do occur, then the answers to them are given in footnotes, or in brief historical references, but they are seldom seriously discussed. Science teachers in general, of course, are the product of textbook-centered teaching. It is therefore not surprising then that they, too, tend to bypass such questions.

Moreover, there is evidence to indicate that many students studying science see little connection between their experiences and ideas about the world and what they learn in science textbooks (Aufshnaiter & Schwedes, 1989). One suspects at the outset that what lies at the heart of this problem is a sense of disconnectedness between the logic of the textbook and what counts for the student as good reasons for believing the science that is presented.

**TEXTBOOK-CENTERED TEACHING AND *NORMAL SCIENCE***

Thomas Kuhn argued in his influential work *The Structure of Scientific Revolutions* (1962) that textbook-centered teaching provides *the* basis for initiation into the *normal science* activity of the working scientist. Indeed, according to Kuhn, textbooks are pedagogic vehicles for the perpetuation of normal science. He stressed that scientists seem to "agree about what it is that every student of the field must know" (1962, p. 44). Though it is generally true that different science textbooks in a given science display different subject matter, they do not differ in substance and conceptual structure.

Moreover, Kuhn believed that scientists learn their science through a study of the application of a theory to some concrete range of natural phenomena, and "never learn concepts, laws, and theories in the abstract and by themselves" (1962, p. 46). Similarly, he maintained, that students of physics learn physics by studying specific applications and concrete examples - what he calls *exemplars* - or "the concrete problem-solutions that students encounter from the start of their scientific education, whether in laboratories, on examinations, or at the end of chapters in science texts" (1962, p. 46). Kuhn noted that rarely do we find in textbooks a description of the sort of problems that the professional may be asked to solve.

Both Kuhn and Whewell promote frequent contact between the *logical-mathematical* and the *evidential-experiential* levels of activity when engaged in sequencing problems. Whewell argued for pre-mathematical experience as evidence for an underlying rule. Kuhn, on the other hand, seems to emphasize post-mathematical formulation, by way of exemplars, to demonstrate the wide applicability of an underlying rule.

For Kuhn the contact between the two planes of activity means being engaged in solving problems based on the commonly recognized exemplars of a science. It should be stressed, however, that Kuhn does not see this activity as the kind of algorithmic problem-solving that seems to be at the heart of conventional science (physics) teaching. Rather, he argues, that " *by doing problems the student learns consequential things about nature*" (p. 188). In elementary physics, for example, these are the problems that are related to such exemplars as the *inclined plane, billiard ball collisions, the conical pendulum* and *Atwood's Machine*. These problems, Kuhn insisted, should be developed and sequenced so that the laws (for example Newton's second law, F= ma) are not seen as a finished product of mathematical formulation to be committed to memory and then applied to problems algorithmically. Rather, Kuhn argues that students should learn to think of such laws as symbolic generalizations that *gain new meanings in different contexts*.

This suggests that Newton's second law, for example, could be introduced first in middle school as a verbal statement given by students. These statements should be based on students' own experiences, observations and intuitive understanding related to motion that can be easily studied, such as the motion of cars, and the motion of dynamic carts. The law then could be reintroduced in senior high school, beginning with a proportionality statement, followed by Newton's own version, namely as force (unbalanced) in terms of rate of change of momentum, and later as the familiar F= ma. The context now is shifted to well-designed experiments, such as the motion of a dynamic cart being pulled by a constant tension that is attached to a ticker timer. Finally, in college, students are introduced to yet another level of symbolic generalization of this law, namely a differential equation, in connection with the solution of the period of a pendulum.

Unfortunately Kuhn's argument that "doing problems is learning consequential things about nature" may be true only in a restricted sense. Only secure science teachers implement such a recommendation by providing mostly consequential problems. The unfortunate consequence for many students is that doing problems means memorizing scientific facts and practicing algorithms.

**A PEDAGOGICAL DILEMMA**

Whewell argued for frequent contact with the *evidential plane* of activity in the teaching of physics. To accomplish this he advocated the explication of concepts by appealing to the student's experience and intuition *prior* to the final mathematical formulation (Whewell, 1850). He seems to have assumed that this would be a straightforward pedagogical task.

Kuhn argues that since textbooks have been so successful in producing competent puzzle-solvers in *normal science*, namely the working scientist, textbook-centered teaching must also be successful in teaching science *in general*, namely the science student. However, some studies suggest that most scientists working today decided to become scientists early in life, *before* encountering textbook-centered science teaching (Aufshnaiter, 1990; Rigden *et al*, 1991). Later, as students, they may see a connection between textbook science and their own self-initiated involvement with scientific ideas (Aufshnaiter *et al*, 1989).

Kuhn is very explicit on this, that by learning the *exemplars* of a science, students should be able to make contact with an evidential base in a way that makes sense to them. It seems, however, that most students fail to make this contact and the normal pattern of science learning is memorization and algorithm-recitation. In other words, students seem to make a clear distinction between school science and everyday science.

One of the reasons for the failure of science teaching to help students make contact with appropriate evidence is that some science teachers have inadequate background knowledge themselves and consequently find it difficult to make connections with the student's evidential-experiential level of activity. While this may not be the case for science specialists in high school it is arguable so in the lower grades, especially in early years science. Another important reason may well be the insufficient attention given to the question of how students learn science concepts.

Clearly, both Whewell and Kuhn are deeply concerned about how students learn concepts in science education. However, neither Whewell's pedagogical emphasis on intuition, geometric reasoning, and pre-algorithm discussions nor Kuhn's account of the role of textbooks and exemplars in science education explicitly discusses the third plane of activity, namely the *psychological plane*. This plane involves activities related to the way students learn concepts in science. Textbooks usually leave the pedagogy, or the question of *how* students learn science, to the science teacher.

In planning successful science teaching, then, science teachers need to pay attention to all three planes of activity, namely, the *logical*, the *evidential*, and the *psychological* (See Figure 1). In preparation for a discussion of how this model (called LEP conceptual model) is used with preservice teachers a brief description of the three planes of activity and how they are related will be given.

## THE LOGICAL PLANE

On this plane of activity one finds the finished conceptual products of a science, such as laws, principles, models, theories, and facts. The conceptions of chemical valence, specific heat, Newton's second law, F= ma, the principle of conservation of energy, the Bohr model of the atom, Mendel's laws of inheritance, the Hardy-Weinberg law in genetics, the *kinetic-molecular theory of gases* and the scientific fact that the electron is the basic electric charge, are all found on the logical plane. (It should be mentioned at this point that the terms "concept" and "conceptions" can be generally regarded as equivalent (Posner, Strike, Hewson, & Gertzog, 1982). However, the terms refer to different levels of conceptualization as will be briefly discussed later).

The basic question on this plane is: "*What operation(s) will link the conception to the evidential plane?*" The answer to this question is important, because it determines to what extent the activity on the *logical* plane relates to the *evidential* plane. I will show later, in preparation for working out an example, that valid operations can range from instrumental to 'paper-and-pencil' operations. So far the examples given have been physics examples. In order to describe the three planes of activity and how they are related, however, general science examples will be necessary (See Figure 1; also see Stinner, 1992). The following examples, one taken from each of physics, chemistry, and biology respectively are good illustrations of the textbook's major preoccupation with the *logical plane.* These are: in physics, the mathematical formulations of *Newton's second law of motion,* in chemistry, the *rules for chemical combination* based on the notion of *valence* of the elements, and in biology, the *circulation of the blood*.

Newton's *second law of motion* is usually given fully developed, with little preamble to the presentation of the mathematical formulation, sometimes as early as grade nine. The *operations* that link the law with the evidential plane are mostly given implicitly in terms of working out textbook problem. Moreover, the kind of questions we asked earlier in connection with this law are seldom posed. Experimental activity, if any, is of the "to verify Newton's second law" type. Students then solve a host of problems from the textbook dealing with motion and forces.

In the chemistry example a definition of *valence* is given and the algorithm for combining such elements as oxygen and hydrogen are laid out. The *operations* that are supposed to connect valence with the evidential plane are usually (inappropriately) given in terms of the Bohr model of the atom and students are taught to relate the number of outer shell electrons with valence. The Bohr model then is supposed to be the evidential connection for the rules of combining elements, but an abstract model like the Bohr model of the atom cannot be considered as evidence. This topic is usually discussed in grade eleven chemistry, but unfortunately it is often taken up in detail as early as in grade eight.

The *circulation of the blood* is generally discussed in grade eight. Students memorize "scientific facts" from diagrams and descriptions in the text. The operations that link the conception to the evidential plane, if given at all, will refer to pumps and closed systems. Sometimes teachers may show large scale models of the circulatory system. Students memorize a great number of facts and study schematics depicting the circulation of the blood. Students must accept, on faith, that the blood circulates throughout the body.

**THE EVIDENTIAL PLANE**

On the evidential plane of activity one finds the experimental, intuitive, experiential connections that support the laws, principles, and facts accumulated on the *logical plane (*See Figure 1). The first question to be asked on this plane is: "*What are good reasons for believing that*...?" Here science teachers should be looking for evidence that "makes sense" to the student. The second question to be asked is: "*What are the diverse connections of this conception*?" On this plane provision needs to be made to show that the concept is valid when used in seemingly disparate areas in scientific inquiry. Moreover, the more diverse connections there are the firmer will be the conception in the student's mind.

Thus, when presenting the topic of motion and forces, essentially Newton's second law, students should be given the opportunity to consider everyday examples of motion. This should be done in response to such questions as: "Do you require a force to produce motion ?" and "What are good reasons for believing that only an unbalanced force produces an acceleration?" In response to such questions simple experiments should be designed, sometimes initiated by the teacher but more often by the student. The typical textbook experiments of the kind "To verify Newton's second law" should be avoided. We should also delay the presentation of the finished product of the mathematical formulation of Newton's laws, such as F=ma.

Before presenting these formulas, however, the teacher should consider the question: "What are the diverse connections that led Newton to his second law?" Historically, there were three empirical connections: the motion of the pendulum, the results of collisions between hardwood balls attached to two pendula, and the motion of the conical pendulum.

These seemingly disparate phenomena were finally united conceptually by essentially one equation. In other words, the results of these experiments plus the scientific imagination of a Newton produced the equation of motion F= ma. Of course, it is not suggested that students should be asked to recapitulate historical high-grade scientific thinking when they are working on the *evidential plane.* However, discussing the evidential basis for the finished mathematical product, such as F= ma, is a splendid science story and can be very motivating as well as illuminating (Stinner, 1993). However Newton's laws of motion are introduced, care must be taken that the teacher does not simply provide the student with the formula without adequate evidential argument, and explicitly say or imply that such laws are inductively arrived at from experimental data alone.

The concept of *valence* is generally taught by introducing *ad hoc* rules for writing simple compounds, such as HCl and $H_2O$, sometimes as early as grade eight or nine. This is done without any evidential basis other than the appeal to the simplified Bohr model of the atom. Science teachers find that students respond to this kind of "evidence" with questions that can be translated to mean: "why should I believe this?" or: "provide me with good reasons for believing..." Unfortunately, some science teachers' stock response here would be: "Hydrogen has one electron in the outer shell and therefore has a valence of +1 and chlorine has seven electrons in the outer shell therefore has a valence of -1 ..." Junior high school students simply do not see the abstract model of the Bohr atom as properly placed on the evidential plane (Vogelezang, 1987). Many students respond with confusion and, ultimately, with boredom.

Again, as in the case of our example of Newton's second law from physics, a historical approach could be appropriate here. The concept of valence was well established and *diversely connected*, long before Bohr's model of the atom was established in 1913. Originally the "combining power" of elements was connected to the two cornerstones of chemistry, namely the principle of conservation of mass, and the law of definite and multiple proportions. To illustrate, these teachers can use ordinary materials found in the kitchen, such as table salt, vinegar, baking soda, Alka Selzer and sugar. Simple preliminary experiments could be devised to show the difference between a mixture and a solutuon, and the difference between a chemical and physical reaction. Later, an experiment showing the chemical combining weights of two elements, for example, that of sulphur and iron, and a demonstration of the *electrolysis of water* can be added. Moreover, the experiments of Gay-Lussac with combining volumes of gases and the theoretical arguments of Avogadro should be discussed. On the basis of such experiments and discussions, and only after a clear (pre-Bohr atom) understanding of the concepts of element and compound has been achieved should the students proceed to write the formulas of simple compounds.

The *circulation of the blood* is studied almost exclusively by memorizing "facts" and schemata from textbooks. The questions one asks on this plane are generally not answered to the satisfaction of the student. For example, most textbooks make little or no attempt to recapitulate Harvey's original arguments of why the blood must circulate. Thus the opportunity to involve the student in one of the first "thought experiments" in biology is missed. Teachers and students could also read and discuss the arguments of Harvey based on a historical setting as depicted in an excellent article by F. Kilgour in *Scientific American* (1956).

A common misunderstanding is that thought experiments are highly theoretical and abstract. However, students find the classic thought experiments in physics often more compelling than concrete demonstrations. Harvey's thought experiment to prove that the blood must circulate is no exception because the arguments appeal to physical principles of conservation of mass (Matthews, 1990, Stinner, 1990).

**THE PSYCHOLOGICAL PLANE**

In this plane science teachers pay attention to the students' pre-scientific knowledge, and to their previous school science. Here we study the responses they have to some key questions we shall pose in testing their readiness to accommodate a concept. Textbooks generally are not directly concerned with the questions asked on this plane. This lack of concern for student prior knowledge suggests that most science teachers engaged in textbook-centered teaching pay little or no attention to how students' preconceptions interact with what is being taught (See Figure 1).

The three key questions on this plane, intended for making connections between the *evidential plane* and the *logical plane,* are based on the work of Posner, Strike, and Hewson (1982) and partly based on suggestions made with regard to the phrasing of subsidiary questions by Hewson and Thorley (1989). The first key question sets the necessary precondition for a conception to be considered at all: the student must find a conception *intelligible* before any meaningful teaching can take place. For example, going back to our first example, a student may not find the mathematical formulation of Newton' second law, namely F= ma intelligible; i.e. he or she cannot solve problems involving F= ma consistently without using a *mnemonic* or without slavishly following an algorithm. Therefore, if the first question cannot be answered with certainty we cannot proceed to the second question which sets the stage for establishing *plausibility.* The student then cannot go beyond meaningless algorithm-recitation on the *logical plane,* since a connection with the *evidential plane* is not possible.

In the chemistry example involving the concept of *valence* teachers encounter similar hurdles. Students in a grade eight class often find the Bohr model unintelligible; that is they simply may not be able to make sense of the connection between an electron state of the outer orbit with the "combining power" of the element when writing chemical formulae. Students also may find the Bohr model not *plausible.* After all, they have no evidential basis for believing in such a model.

The *circulation of the blood* as a conception is found to be intelligible and plausible by most students, especially after a discussion of Harvey's arguments. It is always astounding to see the delight on the faces of fledgling science teachers when they are first exposed to Harvey's simple but compelling thought experiment.

Ideally, of course, one wishes to see every concept carried through to satisfying the requirements of the third question, that of *fruitfulness.* In the physics example, that would mean being able to apply Newton's second law in a wide variety of situations, including *linear motion*, *circular motion* and simple circular satellite motion. In the chemistry example, that might involve the student consciously trying to understand such phenomena as electrolysis, electroplating, and how experimental evidence suggests the concepts of electrovalence and covalence. Finally, in the biology example, the student might want to know how diseases spread throughout the body, what might be the underlying causes of heart attacks and strokes. Only when students can see new connections, perceive a variety of possibilities, and come up with new ideas, is a concept firmly established in the mind of the student.

**PREPARING TO USE THE LEP MODEL**

Preservice teachers in science education at the University of Manitoba have used the three planes of activity for the last three years (what we now simply call the LEP model) for mapping out action plans for teaching concepts and conceptions in science. The following comments are based on experiences and responses of students about the strengths and weaknesses of the model.

First, preservice science education students are presented with arguments that concepts and conceptions are central and are fundamental agents of thought. Secondly, arguments are given and research evidence presented for claiming that sound understanding of science conceptions and concepts cannot be attained from a textbook alone, unless students find a way to link prior knowledge to the new conception presented in the text (Pines & West, 1986; Renner *et al*, 1990; Vachon & Haney, 1991; Wandersee, 1988). Finally, the LEP conceptual model is presented as one instructional strategy to help students as well as teachers to facilitate conceptual development by linking prior knowledge to a new conception in an appropriate way.

To begin, conceptions should be thought to consist of a network of concepts. For example, the conception of Newton's second law of motion subsumes the concepts of force, mass and acceleration by way of a mathematical relationship.

Concepts, in turn, such as mass, velocity, force, comet, atom, density, light year, plate tectonics and kinetic energy, are best thought of as *abstractions that have attributes of regularity or structure that can be represented symbolically* (Novak & Gowan, 1984, p. 15). Rudolf Carnap, an influential contemporary philosopher of science, conveniently divided science concepts into three main groups: *classificatory* (taxonomy in botany), *comparative* (warmer, heavier, longer), and *quantitative* (assigning a number to the weight of an object) (1965, pp. 51-54). The first is qualitative, the second intermediate between qualitative and quantitative, and the third must have clear procedures for assigning a numerical value. Carnap argued that qualitative, comparative concepts are useful, can be operationalized, and are often precursors to quantitative concepts. Thus, the comparative concept "warmer" eventually developed into the quantitative concept "temperature". Similarly, before the concept of weight became a quantitative concept the comparative concepts of heavier, lighter, and equal in weight had to be established. Carnap's ideas of establishing empirical procedures for transforming qualitative concepts to quantitative ones are important for science teachers. These procedures help them guide students from intuitive qualitative concepts to quantitative concepts used in science. Implicit in Carnap's presentation is the use of verbal arguments rooted in personal experience that lead to self confident application of the symbolic representations of science such as Newton's second law.

At this point preservice students are reminded that concepts are generally built up from more elemental notions. For example, the concept of density is based on the special relationship between mass and volume that determines the physical property of *density.* Clearly, mass and volume themselves are concepts, but more elemental than the concept of density. Indeed, the conditions of LEP model require that if these elemental concepts are not intelligible to students then they cannot understand the concept of density (see example worked out in Stinner, 1992).

What, then, are the special requirements for a concept to be acceptable as a scientific concept?

To answer that important question it is recommended that the reader refer to Percy Bridgman (1952) and Gerald Holton (1980) for clarification because of the seminal and important work they did on the nature of science concepts. Bridgman believed "we do not know the meaning of a concept unless we can specify the operations which were used by us or our neighbor in applying the concept in any concrete situation" (Bridgman, p. 3). In other words, for a concept to be *bona fide* scientific a necessary but not sufficient condition is that a concept have an operational aspect. Holton (1980) went further and argued that for a concept in science to be a *bona fide* the concept must be *operationalizable (in one form or another), quantitatively determinable,* and *diversely connected*. In addition, Holton stressed that operationally definable concepts do not by themselves guarantee us a science. Conceptions must also have a quantitative character. Finally, concepts may be quantitative and meaningful, but still not be permissible to be included into science. Concepts must also be connected in a fruitful and consistent way to all aspects of science.

Preservice students generally find that operationalizing a concept like density, or a conception like Newton's second law was the most difficult part of the activity in fulfilling the requirement of the LEP model. Further referral to Bridgman's ideas then clarifies the task of finding an operational statement that links the theoretical (the logical plane) with observational evidence (the evidential plane).

Bridgman, in elucidating the nature of operationalizing science concepts, argued that there are two kinds of valid operations, namely instrumental and non-instrumental. Instrumental operations assign a numerical value to the concept, for example, finding the density of a metal to be 7000 $kg/m^3$. Non-instrumental, or what he called 'mental operations', on the other hand, are represented by 'paper-and-pencil' activities, which may include verbal and mental operations. Moreover, in the non-instrumental category of mental operations one should include the use of models and analogical reasoning.

This approach to operationalizing a concept ensures a wide latitude for establishing a relationship between the logical and evidential planes of activity. Thus, the degree of success of operationalizing such common conceptions as the three examples used (namely Newton's second law, chemical valence, and the circulation of the blood) depends on one's background knowledge, and on one's imagination and ability to construct a plausible pencil-and-paper or verbal argument that may involve models and analogical arguments (See worked-out example in Stinner, 1992).

## SCIENCE TEXTBOOKS, PRESENT PROBLEMS, AND THEIR FUTURE FORM

Many research studies suggests that concepts in science cannot be successfully taught from the textbook alone. Renner *et al* (1990) investigated whether sound understanding of science concepts and conceptions develop from textbook use. They selected four concepts/conceptions from middle school, namely *expansion*, *the Doppler effect*, *flotation*, and *kinetic energy*. Renner *et al* judged the expansion concept concrete and the other three formal, with the *Doppler effect* the most formal. Specifically, they investigated how textbooks can be used to develop theories, skills, and classroom strategies that would promote effective science reading and reading comprehension.

These conceptions are suitable for the LEP model and are among those analyzed by my preservice students. Some have already used this model in junior high school in teaching these very conceptions.

It was not surprising, therefore, that Renner *et al* found that very few junior high school students showed even a partial understanding of the *Doppler effect* and only a few demonstrated a good understanding of the *expansion concept*. In all, they found that when students study the four concepts as given in a textbook, 61% of the students showed no understanding or showed misunderstanding. The combined percentage of partial understandings and sound understandings responses were 28%. They concluded "Those data do not constitute a positive recommendation for using a science textbook as the focus of science teaching nor, in all probability, the manner in which it was used" (p. 51).

Since prior knowledge based on direct experience of the concept or conception to be understood determines the student's comprehension, Renner *et al* recommend laboratory, demonstrations, and other activities *prior* to reading the text. They concluded "teachers can no longer adopt a textbook and follow it straight through" (p. 51).

Science educators generally recognize that science teachers encounter two kinds of knowledge when they are teaching scientific concepts. There is children's *intuitive knowledge*, based on sense-making activities involving the environment as well as interactions with parents, peers, media; and then there is *formal knowledge,* a product of planned instruction, or what we generally call *school science* (Pines & West, 1986).

Flick (1991) also reminds science teachers that they must pay attention to these two ways of knowing. Students are expected to formulate new ideas in terms introduced by the textbook. However, forcing students to think in textbook terms separates the use of direct experience into two categories, namely the experiences that are used to support personal beliefs and those used as referents for scientific meanings.

Wandersee (1988) found that even at the college level only 6% of students in his study made a conscious effort to link prior knowledge to the new concepts when they were reading a textbook. Since most science teaching is textbook-centered on the college level Wandersee recommends, for one thing among others, that instructors "teach students to consciously attempt to link new concepts in a textbook to prior knowledge" (p. 81).

Finally, Chiappetta, Sethna, and Fillman (1991) analyzed a wide range of science textbooks from grades seven through to twelve. In evaluating these textbooks they used four categories of scientific literacy, (1) *the knowledge of science*, (2) *the investigative nature of science*, (3) *science as a way of thinking,* and (4) *interaction of science, technology, and society.* The first category involves "facts, concepts, principles, laws, theories, etc...the transmission of scientific knowledge where the student received information" (p. 943). The second category refers to "the intent of the text to stimulate thinking and doing by asking the student to 'find out'" (p. 943). The third category is connected with the intent of the text to illustrate "how science in general or a certain scientist in particular went about 'finding out'" (p. 943). The last category is checked if "the intent of the text is to illustrate the effects or impacts of science on society" (p. 944).

It is relevant to discuss briefly the detailed results of investigating high school chemistry textbooks in this study. It was found (not surprisingly) that the first category, the knowledge of science involving *facts, principles, and laws*..., typifies the content of most of these textbooks (about 70% to 90%), namely the transmission of information to be learned by the student. Only about 15% of texts were devoted to category two, namely *the investigative nature of science*. Category three, *science as a way of thinking*, was very poorly represented, ranging from 0% to 6%. Finally, category four, *the STS connection*, ranged between 4% and 12%. It is probably safe to conjecture that physics and biology textbooks would not fair much better.

Clearly, the first catagory of science literacy as outlined by Chiappetta *et al* is related to the logical plane in the LEP model. The second category can be roughly compared to the evidential plane in the LEP model. To a great extent the evidential plane also accommodates the third category, because a complete evidential argument in response to the question "What are good reasons to believe that...?" almost always connects to an historical account of the idea discussed. The second question on the evidential plane, "What are the diverse connections of the concept or conception?" pays attention to the STS connection.

The findings of the research reviewed point to a general failure of textbook-centered science teaching. What then must be done to raise teachers' awareness of this issue and bring about significant change in curriculum design?

My preservice students' have attempted to use the LEP model in the teaching of main conceptions and concepts in science in middle school. We have gathered evidence, based on individual and group discussions prior to and after the use of the model, that pre-service teachers first develop a good awareness of the above dimensions of scientific literacy. Later, and more significantly, they seem to develop better ideas of how to engage students' preconceptions, set realistic goals for the acquisition of conceptions and ensure student involvement. What remains to be done is to assess the impact of teaching in actual classroom setting. In order to formalize the use of the model and obtain a data base for classroom application a summer institute for in-service teachers is planned for 1994, to be followed by field testing in the schools.

We are now hypothesizing that science instruction in a real classroom setting can be significantly enhanced and enriched by the systematic use of the LEP model. Essentially, the model will engage the teacher in four activities, namely (1) referring to the preconceptions of students and testing for their readiness for conceptual change (psychological plane), (2) examining the statements made in the textbook (logical plane) and providing evidence for these statements (evidential plane), (3) finding diverse connections in science and technology (evidential plane), and finally (4) working with the model will also engage the teacher in narrating the historical development of an idea. This discussion then points to the need to change the present form of the science textbook, beginning with the recognition of science teachers of the general failure of textbooks to significantly address and coherently incorporate three kinds of knowledge:

1. the findings of modern learning theories about the nature of the learning process, especially the importance of paying attention to students' preconceptions, to identify them, respect them, and then to build on them,

2. the contemporary picture of the nature of science, especially the understanding that scientific conceptions, principles, theories and laws are not enshrined but are evolving, that they do not follow simply from observation in an inductivist manner,

3. the diverse connections between scientific conceptions and discoveries *and* technology and society,

Textbook writers should take this knowledge into account in shaping the textbook of the future. Briefly going beyond the framework of this discussion, one hopes that they will also reconsider the rhetorical language of textbook writing. Strube (1989) has investigated the language of physics textbooks. He recommends that textbook writers pay attention to style, assume less formality and project more warmth, place more emphasis on verbal argumentation, and reduce the number of new terms introduced. He found that authors are generally remote and anonymous, tend to overemphasize logical arguments, using a style that is rigid and inappropriate to the students' world, providing the student with definitions that are short and easy to remember while explanations given are long and complex.

Textbook writers also should temper their tendency to give logical and rational reconstruction of scientific discoveries and theory-building with the humanizing effect of using actual case studies. Sutton (1989) as well as Stinner and Williams (1993) focused on the interplay of experiments and theory in science textbooks. They recommend case histories to dispel textbooks' message that, if appropriate experiments are carried out, discoveries are sure to follow. Finally, textbook writers should incorporate existing and emerging technologies with pedagogically sound suggestions as to how they can be used.

There are already hopeful signs that such recommendations are being considered in designing science textbooks. Recently, Duit, Haussler, Lauterbach, Mikelsis, & Westphal (1993) have published a newly designed textbook for elementary physics that specifically pays attention to the LEP conceptual model discussed in this paper as well as to the recommendations made by Strube and Sutton. The textbook also implements a constructivist, conceptual-change model that takes into account students' prior conceptions.

**IMPLICATIONS FOR SCIENCE EDUCATION**

The habitual use of a conceptual model in the the teaching of science, such as the LEP conceptual model, in conjunction with present teaching aids and materials, seems to make teachers aware of the proper role of textbooks. They also begin systematically to refer to what learning theories say about concept formation and become aware of the importance of what the historians and philosophers have said about the nature of science.

The modest expectation of the application of the LEP conceptual model approach is that teachers reflect on the conception or concept they are about to teach, its place, origin, its relationship to the theoretical background, and operationally link the conception to the evidential plane. This reflection should encourage teachers to collect appropriate evidence that "makes sense" to the student, in answer to the questions "What are good reasons for believing that..?" and to " What are the diverse connections of the concept?" Finally, it is hoped that teachers would map out the many connections between the activities on the *evidential* and the *logical planes*, filtered through the requirements of the *psychological* plane (see detailed example worked out in Stinner, 1992).

Teachers must venture beyond a simplistic understanding of science as an empirical-inductive enterprise. This could be accomplished by encouraging teachers to frequently consider the three planes of activity outlined here. In addition, the use of the LEP model will also encourage teachers to consult diverse texts and other sources that deal with historical contexts and philosophical issues of science. Finally, science teachers should collaborate with their colleagues on an on-going basis in finding new and fresh evidential material. Implicit in this approach, for example, is the need to clarify relationships between *experiment, hypothesis* and *theory* in scientific inquiry. The use of the LEP conceptual model as a *heuristic* device then allows an eclectic discussion of the philosophical issues that would be independent of a school of thought. Repeated excursions into historical background will surely generate interest for the teacher and the student alike.

Indeed, one of the strengths of making contact with the evidential plane is that it *inevitably draws us into a historical consideration of the origin of a concept.* This was the case with each of the examples we discussed: Newton's second law of motion in physics, the concept of valence in chemistry, and the notion of circulation of the blood in biology. In each case, the teacher would be encouraged to research the historical contexts to provide appropriate evidence for what the students are given on the *logical* plane. This kind of activity and reflection would influence the teacher and change his or her view and understanding of science. In fact, one could claim, that by using this approach "science teachers are being challenged to present science as it 'really' is, rather than promote a mythic, textbook science" (Martin & Brouwer, 1990, p. 554).

The textbook of the future will need to consciously incorporate the findings of the history and philosophy of science as well as those of contemporary learning theories, along the lines suggested by this discussion. To achieve that, textbook writers must use a model for conceptual change, such as the LEP model, that guides them toward developing an appropriate format and suggesting a new role for the science textbook. Such a model should make connections with the findings of the history and philosophy of science as well as contemporary learning theories. However, these connections should appear to be 'natural', an intrinsic part of the "story-line" of the presentation, and not related in separate blocks as an aside, placed there only for interested students to consider.

Perhaps what we need is a new version of the widely used PSSC physics text of the 1960's that physics teachers enjoyed but students generally found difficult to read. The new version must challenge teachers as well as make the material interesting and motivating to students. One way this can be done is by contextual teaching involving computers and making STS connections that are necessary part of the development (Stinner and Williams, 1993).

The textbook will probably be with us for some time to come. It may even be *necessary* for the education of the scientist, as some writers seem to believe (Brackenridge, 1989). Textbook-centered teaching, however, is not *sufficient* in producing the scientist who will easily discover a fresh approach or educate the layman who will be scientifically literate. To achieve that, science teachers must recognize and understand the two-way passage from the logical plane to the evidential plane, filtered through the requirements of the psychological plane. Recognition and understanding of this passage by textbook writers may change the format and the role of textbooks in the future.

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# Chapter 8

## Toward a More Humanistic Science Education



**Contextual teaching in science: from science stories to large context problems.**

**Introduction**

In his works, Plato outlined two basic problems of inquiry, one dealing with the interrogation of nature and the other with the interrogation of man. The first, often referred to as "Plato's problem", was a direct question that set the direction of research programs in astronomy and science that eventually produced the Ptolemaic system and later Kepler's laws of motion. Plato "set his pupils in the Academy the task of working out a system of geometrical hypotheses which, by substituting uniform and circular movements for the apparently irregular movements of the heavenly bodies would make it possible to explain the latter in terms of the former - in his own famous phrase, to 'save the phenomena'" (cited in Holton, 1980).

Indeed Holton (1980) argues that the Platonic problem is concerned with three elements that modern science still deals with: namely, the interplay between "facts" of observation, a plausible "story" to order our observations, and, finally, a resolution of the puzzle by the imaginative construction of what Holton calls a mathematical and/or physical *analogon*.

The second problem, often referred to as "Plato's dilemma", delineated the paradox between the claim that "the meaning is in the text" and the requirement that writing (or any argument) must stand up to a dialogical encounter, being a response to the question "what do you mean?", as the only way to acquire true knowledge. Essentially, Plato attacked the rhetoreticians who discouraged questioning altogether and wanted only to disseminate their ideas, not "to discover truth in mutual dialogue" (Gee, 1988). Since dialogical encounter is essential for clarification of the text, writing as a mode of transmission of knowledge was problematic for Plato. Indeed, hermeneutics, a branch of scholarship devoted to the theory and practice of the interpretation of texts, still deals with this problem today. In science education, too, it is now commonplace to espouse the constructivists' view that students construct their own world. Therefore, reading a text and being able to repeat what the text said, even in the context of successful problem solving, does not constitute true knowledge. The question of textual interpretation thus becomes important in the sciences -and elsewhere - and dialogical encounters between students and teachers and between students and other students is now seen as pedagogically sound practice.

It can be argued that Plato's two problems foreshadowed the later separation between the sciences and the humanities, first in the middle ages and then as we see it today. The problem of the separation between the sciences and the humanities was again outlined by the two cultures theory of C.P. Snow (Stinner, 1989). This theory (Snow, 1959) is based on the assumption that the intellectual life in Western society is increasingly being split into two polar groups, namely the scientists and the humanists. Between these groups a gulf of mutual incomprehension exists. One culture, the scientific, should be thought of as continually in flux, incorporating new discoveries on the basis of general agreement and verifiability. The other culture, the humanistic, changes but does not depend on collective agreement since its emphasis is on content not process.

If Snow's picture of science is correct then the problem of what it is to be literate in the sciences and the humanities consists in specifying the "pillars" of each scientific and humanistic discipline, then determining how these pillars are related, and finally suggesting ways of bridging the gap between them.

In a deeper analysis of the problem, however, we should first look at the language of science and relate it to the language of the humanities. One commonly thinks that science uses a language that consists of *specialized words* and *mathematics.* The words are thought to be part of "scientific English", a special terminology that is found in the finished product of scientific reports, while the mathematics science uses is thought to be imbedded in a scientific deductive system, designed for total, objective and unambiguous descriptive and explanatory communication. Literature, which is central to the humanities, however, is thought of as using a language of words only, designed for subjective, ambiguous, and metaphorical communication.

Science as an activity, however, cannot be pinned down by a specifiable general method, contrary to what Snow seems to have suggested. As Jacob Bronowski so eloquently argued (Bronowski,  ), high-grade thinking in science involves a creative action utterly dependent on human imagination, not unlike that involved in the creativity associated with artistic and humanistic activities. Moreover, the great stories of discovery in science show that scientific activity, too, is characterized by subjectivity, sudden unaccountable insight, ambiguity, and the need not only for analogical, but also metaphorical description and communication.

I will argue that in the early years *science stories* should be used in the classroom to show the diverse connections between the sciences and the humanities that enrich conceptualization can effectively be established in a multidisciplinary context of the science story that attracts the student**.** For the middle years and the senior years we should design contexts that generate questions and problems that naturally involve both the humanities and the sciences. Contextual teaching of this variety can be thought of as a response to the quest to "bridge the gap" between the sciences and the humanities. However, this must be accomplished in a less contrived way than is possible in courses such as "poetry for physics students" or "physics for poetry students".

The main question then becomes: "Can we reorganize the science curriculum around contexts and science stories that serve to motivate students, help them learn the central science concepts "naturally", and develop understanding that is rooted in both scientific and humanistic traditions?" The essential goal would be to escape textbook centered teaching that enshrines the separation between the humanities and the sciences.

**The Context-content paradox**

It is a truism that appropriately designed contexts which attract students' interest create great motivation to learn science. For example, *The Story of Flight* could be one of three or four contexts designed for a grade nine class to study elementary mechanics in physics that involves simple kinematics and forces. Students choose one context and work together in small groups. They discuss the questions and problems this context generates, decide which ones interested them and then go about working out answers. Their task is to present answers, provide solutions to the group, relate them to answers provided by the other members, and ask new questions. The teachers role would be that of a research partner who guides, clarifies, questions and makes suggestions.

It is clear that at the heart of this kind of motivation lies self-initiated activity that helps students to experience meaningful learning. Students who are engaged in such activities generally judge the studying of science as meaningful, interesting and relevant (Aufshnaiter, 1989). This is especially true if the context is mapped out and the questions and problems are generated in collaboration with the teacher and other students (Stinner and Williams, 1993).

We can regard the provision of such contexts as a necessary but not sufficient condition for successful science teaching. We must ensure that a number of other conditions are satisfied before we can expect students to consider the learning of science interesting and relevant that leads to meaningful learning. First, in addition to attracting the students' interest with appropriate contexts, the questions and the problems that are generated from the context must seem "real" and make sense to the students. Secondly, we must make sure that, at the beginning, students are be able to answer a few questions and solve a number of problems with relative ease. Of course, students will soon face questions that they cannot answer fully, and problems they cannot solve completely. This is the crucial stage in contextual learning. Now group discussion and guidance by the teacher are essential in motivating students to learn new relevant content for successfully dealing with those questions and problems.

Conventionally we teach the content[1] (I am assuming that "content" included "processes" of science) of science first and then have students test their understanding of the material by asking them to solve contrived "mini-contexts", generally called "type problems" at the end of chapters. Textbook-centered teaching has been the driving force behind this approach to science teaching since William Whewell published his physics textbooks more than 160 years ago (Stinner, 1992).

Kuhn seems to be referring to this kind of teaching when he argues that scientists learn their science through a study of the application of a theory to some concrete range of natural phenomena.

Indeed, he insists that "scientist never learn concepts, laws, and theories in the abstract and by themselves,... after the student has done many problems, he may gain added facility by solving more. But at the start and for some time after, *doing problems is learning consequential things about nature*" (Kuhn, 1962, p. 187).

I have argued elsewhere (Stinner, 1992) that when Kuhn speaks of this kind of an ongoing content-context interaction, namely, between what he calls "theory" and the recognized exemplars of physics, he is referring to the education of 'normal scientists' (practicing research scientists), and not to the education of science students in general. I have further argued that for most science students frequent contact with type problems is an activity that seldom ensures that the student learns *consequential things about nature*. Rather, it guarantees that students will see science (physics) as a difficult, algorithmic problem solving activity that is unrelated to the "real world". This

activity seems to be at the heart of conventional science (physics) teaching (Stinner, 1992, Rigden, 1991, Von Bayer, 1991).

It may be that for future scientists the steady diet of the solving of problems at the end of chapters is, if not an intrinsically motivating activity, at least a pleasurable one. In fact some studies suggest most scientists working today (Kuhn's normal scientists) decided to become scientists early in life, *before* encountering textbook-centered science teaching (Aufshnaiter, 1989, Rigden, 1991). Later, as secondary school students, they perhaps see a connection between textbook science and their own self-initiated involvement with scientific ideas (Aufshnaiter, 1989).

A general problem then emerges whenever teachers try to escape from textbook-centered teaching to teaching science by way of contexts that attract students. In order to solve the problems generated by the context students already had to have mastered a large body of content! For example, when we attract the physics student to answer the questions and problems generated by such contexts as "Physics of Star Trek" and "Physics on the Moon" we must ensure that the student has sufficient content knowledge to tackle successfully at least some of the problems. If the student is unable to do that mush he/she will become discouraged and looses interest.

Science teachers encounter the same problem in junior high school, whenever contextual science teaching is undertaken. For example, in teaching elmentary physics in a context called *The Story of Flight* the student is expected to have already learned a considerable amount of content knowledge in mathematics, physics and some chemistry. Questions and problems that the context generates are usually framed by the textbook and the teacher, not the student. A great deal of self-initiating involvement then is lost at the very beginning of the activity.

The interaction between content and context then presents us with a pedagogical problem. I would like to call this the **content-context paradox.** We could summerize this paradox this way:

To motivate students to acquire sensible content knowledge we set contexts that attract them. However, students cannot deal with the questions and the problems that the context generates unless they already have some content knowledge!

How then can we ensure that students acquire content knowledge in science?

Conventionally we teach science (physics, biology and chemistry) within a rigorous textbook-centered approach, using problems that are more or less contrived to emphasize the content of the textbook.

How then can we make ongoing provision for context-based science teaching to motivate students to learn the content?

Our mandate as science educators is to ensure that students are motivated to acquire the content knowledge "naturally" in dealing with the problems and issues generated by the context. Of course, we may not be able to present all of the content knowledge to students in a motivational contextual form.

I recommend early introduction to science by way of contextual teaching, that includes science stories and story-like approaches.

The ideal, of course, would be to provide the motivational context and then relevantly use textbooks as references in answering the questions and solving the problems the context generates. Our final aim would be to have students say, when they finally encounter Newton's second law or the law of definite proportions formally: "Of course, how could it be otherwise?"

Ultimately one can envisage science being taught by way of contextual teaching from elementary grades right up to high school. In an ideal world, contextual teaching based on a "story line" could go on until specialization would seem to be inevitable. In such a world, textbooks would have to be rewritten and their role reconsidered.

There is a perceived split between the humanities and the sciences that is seen as having established two distinct and identifiable modes of thought. This split arguably can be traced back to Plato, but the significant parting of the ways occurred in the fifteenth century. There have been several reexaminations of the implications of this separation since then (Stinner, 1991). The latest public manifestation of it appeared just over thirty years ago in C.P. Snow's "two cultures" theory and F.R. Leavis' response to it (Stinner, 1989). What is of concern is that this separation seems to be institutionalized, is enshrined in our textbooks and consciously incorporated in our curricula. I will suggest that the science story, as described in this paper, may offer a partial reconciliation between the two modes of thought.

Unfortunately, many science teachers believe that science is monolithic and is based on inductive-empirical evidence. They also believe that there is a specifiable scientific method, unique to the sciences and foreign to the humanities, that can be taught across the scientific disciplines. Moreover, many are convinced that only this method will lead to progress and that it clearly demarcates between humanistic and scientific activities. This set of beliefs implies one kind of science curriculum and science teaching.

However, it can be argued that in fact there is no specifiable scientific method that can be taught across the scientific disciplines and that scientific concepts and theories do not follow from observation in a simple inductivist manner, because we see the world through our prior knowledge and through our ideas. Moreover, one could claim that scientific knowledge is actually tentative and that new knowledge is produced by the creative act of the human imagination allied with a variety of methods of scientific inquiry. Finally, we could take the position that there is in reality no clear demarcation between the creative act in the sciences and in the humanities. This general set of beliefs would produce quite a different kind of science curriculum and science teaching.

I will argue that preparing students of science education to teach science in a way that takes into account both the sciences and the humanities requires more than a cursory acquaintance with the relationship between these human activities. Moreover, I will argue that, to that end, science teachers must be able to develop their own *science stories* that take into account this relationship and be able to show facility in using them in a classroom. Ultimately these *science stories* should be used in the classroom to provide appropriate evidence toward conceptualization that appears to the student not only to be intelligible, plausible and fruitful (Posner et al, 1982) but also rich, diverse and motivating. My hypothesis is that diverse connections between the sciences and the humanities that enrich conceptualization can effectively be established in a multidisciplinary context of the science story that attracts the student.

Our appropriate aim should be to introduce children to science, much the same way as they have been "inducted into full membership of their culture" (Egan, 1988). I would like to take up the challenge contained in Egan's plausible suggestion "that the role of the story or the shaping narrative is becoming increasingly recognized in all subject areas, *even in the sciences,* which had once seen themselves as positivistically immune from subjective shaping" (Egan, 1988).

**Snow's Two Cultures**

The most recent public confrontation between the sciences and the humanities was initiated by the two cultures theory of C.P. Snow (Stinner, 1989). This theory (1959) is based on the assumption that the intellectual life in Western society is increasingly being split into two polar groups, namely the scientists and the humanists. Between these groups a gulf of mutual incomprehension exists. One culture, the scientific, should be thought of as continually in flux, incorporating new discoveries on the basis of general agreement and verifiability. The other culture, the humanistic, changes but does not depend on collective agreement since its emphasis is on content not process.

Specifically, Snow claimed that the humanist is more often illiterate in the sciences than the scientist is in the humanities. In order to remedy this situation he advocated the acquisition of cores of knowledge as the basis for both scientific and humanistic literacy. For example, it was axiomatic for Snow that there are scientific equivalents to the questions, "Can you read?", "Do you understand Shakespeare?" The scientific equivalent to these are "Do you understand Newton's laws of motion?", and "Do you understand the second law of thermodynamics?". Later in his argument Snow concluded that the teaching of the humanities must ultimately be subsumed by the demands of the scientific revolution.

If Snow's picture of science is correct then the problem of what it is to be literate in the sciences and the humanities consists in specifying the "pillars" of each scientific and humanistic discipline, then determining how these pillars are related, and finally suggesting ways of bridging the gap between them.

In a deeper analysis of the problem, however, we should first look at the language of science and relate it to the language of the humanities. One commonly thinks that science uses a language that consists of *specialized words* and *mathematics.* The words are thought to be part of "scientific English", a special terminology that is found in the finished product of scientific reports, while the mathematics science uses is thought to be imbedded in a scientific deductive system, designed for total, objective and unambiguous descriptive and explanatory communication. Literature, which is central to the humanities, however, is thought of as using a language of words only, designed for subjective, ambiguous, and metaphorical communication.

Science as an activity, however, cannot be pinned down by a specifiable general method, contrary to what Snow seems to have suggested. As Jacob Bronowski so eloquently argued (Bronowski, ), high-grade thinking in science involves a creative action utterly dependent on human imagination, not unlike that involved in the creativity associated with artistic and humanistic activities. Moreover, as we shall see, the great stories of discovery in science show that scientific activity, too, is characterized by subjectivity, sudden unaccountable insight, ambiguity, and the need not only for analogical, but also metaphorical description and communication.

As a science educator I am interested in designing contexts that generate questions and problems that naturally involve both the humanities and the sciences. Contextual teaching of this variety can be thought of as a response to the quest to "bridge the gap" between the sciences and the humanities. However, this must be accomplished in a less contrived way than is possible in courses such as "poetry for physics students" or "physics for poetry students". Finally, I am interested in what kinds of scientific and humanistic literacy recognizes a common ground between the sciences and the humanities.

Snow might have disagreed with this simplistic picture of the nature and role of science, but it is clear that we do teach science *and* the humanities *as if* we subscribed to the a *pillar* theory of knowledge. What concerns me as a science educator, however, is that the notion of an inherent division between the sciences and the humanities is generally regarded as self-evident and seems, unfortunately, to be irreconcilably institutionalized in the curriculum.

My belief is that science stories may provide a common ground in which the sciences and the humanities can coexist. I will first describe the historically-placed science story and later identify a number of other story-like approaches. I will then outline a program of contextual teaching using the historically-placed science story as well as such story-like approaches that connect the sciences and the humanities until specialization seems inevitable. Moreover, I will argue that early introduction to such story-like approaches might ensure that students get a contextual understanding of basic ideas in science that is rooted in the sciences as well as in the humanities. My modest hope is that this kind of contextual understanding will make students humanistically and scientifically more literate and prepare them better for specialist learning in the senior years than the conventional textbook approach can achieve.

**Science Stories**

All of us know the story of how Archimedes was able to solve Hiero's problem of the crown after sitting in a tub at a public bath. Physics textbooks tell us that Galileo tested free fall by dropping two different weights from the Leaning Tower of Pisa. Newton is said to have gained great insight into the mysteries of universal gravitation while sitting under an apple tree, reflecting on the nature of gravity. Chemistry textbooks like telling students how Friedrich Kekule thought of the shape of the ring structure of the benzene molecule: by his own account the image came to him while falling asleep and watching the snake-like dancing of the flames in front of an open fire place. Finally, Einstein in his memoirs remembers that as a sixteen-year-old he imagined himself riding on a "light wave", asking what the consequences were of doing so. The answer to these questions later laid the foundation to the special theory of relativity.

The stories behind these brief statements are examples that celebrate the moment of creative insight, commonly known as the "aha-experience". The paradigmatic example of such experiences, of course, is Archimedes' discovery of the law of flotation. Less known modern examples of scientific insights, to name only a few, are Pasteur's brilliant solution to the problem of spontaneous generation, Fleming's recognition of the antibiotic enzyme lysozyme, Fermi's postulate of the massless neutrino, and Watson's and Crick's envisaging of the helical structure of the DNA molecule, life's master molecule, arguably the ultimate "eureka-experience" so far.

I challenge my student teachers to pick one of these brief statements and ask them to a write a "science story" that is suitable for teaching in a middle-years classroom. It is great fun, as well as being instructive, to collaborate in the writing of such stories. My students have written many science stories, variously sometimes also labelled "case studies", or "large context problems". I am now involved in a computer centered multimedia project, appropriately entitled "Eureka Project" where we dramatize the discovery of the three laws of physics known to the Greeks (the law of reflection, the law of flotation, and the law of levers). The science of the Greeks, because it is essentially high-grade thinking based on unaided observation, seems especially well suited for teaching elementary years science.

Indeed, timing may be important in introducing to the student concepts and experiments in science. In fact, one can argue that the "teachable moment" of the historical context in science is precisely at this time (6-14 years) and perhaps again in graduate school. If we introduce them too early we will encounter problems because intellectually students are not ready. If we introduce them too late "children's science can ossify into layman's science,...showing little or no motivation to change their present view" (Osborne *et al*). Science teachers in high school know that it is very difficult to teach science in historical context because, as Kuhn has pointed out, "students know what all the answers are" (Kuhn, 1962).

In the Eureka Project we are attempting to connect three stories of discovery in one setting that has one major unifying idea that attracts the student. We are looking for a good story line placed in historical context in which the big science questions of the times arise naturally. We will then create a context with a dramatic tension that requires a resolution. In addition, we should remember that at this age the visual and theatrical component of teaching is important.

Although it is important to be "historically correct", poetic license can be taken in designing the story (remember that the story of the Leaning Tower of Pisa is apocryphal). We want to give students the opportunity to choose one of several solutions to the story line. Each of these solutions then will lead to one of a number of blind alleys but will ultimately connect to one of several plausible "eureka experiences". Our approach is modelled somewhat after the currently popular role-playing computer games. We want to ensure the uniqueness of the personal involvement of the student and make provision for both humanistic and scientific creativity. Students will be encouraged to respond with verbal arguments rather than just repeat textbook definitions. However, students will not be working with the computer all the time. Occasionally they will be asked to leave the computer and discuss ideas, discoveries, problems in groups as well as perform simple experiments.

As the student progresses, further connections will be made with the ideas of Pythagoras, Euclid, and Aristotle. However, we must not forget the mythological and metaphysical connections of Greek science. As Egan has recently shown, scientific ideas can readily be connected with Greek mythology in a story form (Egan, 1990). Throughout the science story we plan to encourage students to make connections between scientific ideas and Greek mythology, drama and art. Finally, we must ensure that the major ideas, concepts and problems of the topic are generated by the context naturally; that it will include those ideas, concepts, and problems that students would learn piece-meal in a conventional textbook-centered approach. The Eureka Project science story then will serve as the prototype science story for other historical settings. Examples of such settings would be:

The Ptolemaic solar system, A day in the life of an alchemist, Galileo's inclined plane experiment, A day in the life of Robert Hook, FRS, The confrontation between Priestley and Lavoisier over oxygen, Dalton's assumptions, his observations and his experiments which led to his atomic theory of matter, Faraday's electromagnetic induction, and Darwin's The Voyage of the Beagle as a background to his theory of evolution.

Science textbooks include stories such as these only in passing. When they are mentioned at all they seldom go beyond the cursory one paragraph statement. What is disturbing from a pedagogical point of view is that they are almost never connected to the development of the ideas in the text. What is still worse, they are seldom well connected to the prevailing scientific and humanistic thoughts of the historical period. The implication is that the business of science teaching is to teach scientists' science (textbook science) and that science stories are at best pleasant diversions that do not serve to enlarge the scientific education of the student.

Science, of course, is more than a collection of aha-experiences - it cannot be reduced to a series of dramatic insights. The vignette of depicting the moment of insight does little to contribute to our understanding of the scientific creative process. However, a good understanding of the events and the ideas that, at least in retrospect, made that event seem almost inevitable, is probably necessary for our complete understanding of the creative element in science. Moreover, scientific work is difficult, often arduous and boring, with diverse connections that only the initiated really understand. However, I am arguing that the dramatizations of key achievements, such as the ones we mentioned, can provide great motivational settings in which to study science, especially in the middle years.

Recent research in information processing suggests that we process information holistically and interpret information uniquely and individualistically (Herrold, 1989). This suggests that artists, writers, as well as scientists engage both the analytical and intuitive capabilities of the brain. These findings further suggest that we should avoid what Goodlad found to be universally applied "narrow range of teaching practices" such as lectures, monitored seat work and rote learning. These teaching practices, he argues, do not "connect students with the structure and ways of thinking" that is required for a deep understanding in any field of study" (Goodlad, 1984). Smith, in fact sees the brain "as an avid story teller and consumer of stories. It is essentially by generating and comprehending narratives that the brain makes sense of the world and operates on it" (Smith, 1987). According to Herrold, Smith is advocating the story format that is cognitively and emotionally involving in place of teaching isolated skills and facts (Herrold, 1989).

Another widely-read educator who recommends that we consciously incorporate stories in education is Egan. He believes that even those who use stories regularly in primary school education "often fail to see that underlying them is a tool of immense power and importance for education. It is a tool that is under-used if it is wheeled out only during story-times that are separated from `real learning' and academic `work'" (Egan, 1988 , p. 104).

Moreover, he has argues against the dominant objectives-based procedures of curriculum planning and recommends a procedure based on the story form. His argument is that the story metaphor is more appropriate in describing what we learn about the world, according to research based on "constructivist nature of human sense making" (Egan, 1986).

Egan maintains that children's understanding of the world is not only affective and moral but logical and rational as well. In the young "thinking and feeling have not yet been schooled down divergent paths" (p. 103). In writing stories in general for education and science stories in particular "we must *find what is most important about the topic and frame that importance in the form which children are predisposed to find engaging and meaningful* (Italics mine", p. 117). Finally, Egen insists that "mathematics and science need to be embedded in contexts of human meaning, with their hopes fears and intentions..." (p. 117).

Many other researchers, science educators and philosophers of education believe that telling a coherent story, with a beginning, a middle, and a provisional end, may be the best way for learning, remembering and re-telling ideas (Kenealy, 1989, Arons, 1989, Luhl, 1990, Egan, 1986, Wandersee, 1990).

Howard Gardner's pluralistic view of multiple intelligences also supports contextual teaching of the narrative kind. He stresses the different abilities among children and "the need for youngsters to have opportunities to find and develop their talents". He is against "curricula dominated by linguistic and logical-mathematical thinking" and sees a "need for rich thematic curricula to evoke a variety of intelligences" (Gardner, 1989, p. 290).

In summary, I am advocating that an appropriately designed science story provide an integrated approach to teaching that emphasizes diverse connections between the humanities and sciences <u>and</u> encourages an individual's attraction to an aspect of the world. In addition, science stories must consciously incorporate a `scientific element' and a `humanistic element'. Even for the simple retelling of "eureka stories", as I have briefly outlined, the crafting of the story is a humanistically creative process. Thomas Kuhn has taught us, however, that we must resist the temptation to present a "logically reconstructed" history according to what seems reasonable to us today. We can invent stories but they must be well placed in history. The proper historical placing requires that events, ideas, and experiments should be plausible in a given historical setting. Thus, a poetic license allows us to send a student from the 20th century back to the third century B.C. but we cannot allow him/her to take back in time a pocket calculator to impress Archimedes.

On the other hand, this restriction may not be appropriate or necessary in early-years science. Bruno Bettelheim showed us that fairy tales are powerful vehicles in capturing and shaping the imagination of the young mind (Bettelheim, 1976) and G.K. Chesterton gave us a convincing argument of the internal logical consistency of the fairy tale in his "The Logic of Elfland" (Chesterton, 1953). The final version of the "science story" then might include those that are based in historical context and those that are free invention or application of the science-educator inspired by both the humanistic and scientific disciplines.

**Some Practical Questions**

Before setting down some conclusions I would like to consider some of the questions that were asked at a recent presentation of the original version of this paper at the University of Auckland in New Zealand. I found these questions challenging at the time and upon reconsidering my original responses to them I think it would be appropriate to place them at this point of my discussion.

<u>1. How would one incorporate science fiction into science stories?</u> I have used the popular TV series <u>The Six Million Dollar Man</u> and <u>Star Trek</u>, cast in story form, since about 1978 (see Stinner, 1980, 1981, 1982) with much success in both teaching high school physics and the preparation of student teachers at the university level. These two popular series lent themselves naturally to setting up problem situations that physics students found more interesting than the solving of similar problems in textbooks. Moreover, in <u>Star Trek</u>, one could quite readily treat such speculative areas as 'faster than light motion' using legitimate physics, sometimes called "tachyon physics". Similarly, after discussing <u>The Six Million Dollar Man</u> the bionics of robots working on the moon and on planets is a very productive extension of

the story. Students love solving such exotic problems - it gives them a feeling of being at the very forefront of science. It is important to mention that the outcome of the story here is not predictable - the outcome is different for each student. Thus different conclusions can be achieved by different students all within legitimate laws of physics, albeit extended to the yet fantasy world of negative masses and faster-than-the-speed-of-light spaceships.

How could we then use such stories as Star Trek to teach effective science in earlier grades? Clearly, here we would have to emphasize the action and the drama. However it is done, I believe that we must pay attention to and build on students' *gut science* (based on intuition and spontaneous reaction) and *lay science* (based on the everyday use of language and media images) and how we can improve the transition to *scientists' science (Osborne, 1984). Thus the stories should provide ample opportunity for students to test their personal science in the context of a well designed story of action and drama.* As in the currently popular computer role-playing games we should pay attention to the individuality of the student. The main objective of these stories should be to provide what Whitehead called the stage of romance for an aspect of the world that appeals to the student. Provision should also be made for them to reach the precision stage where the consequences of their apprehensions can be worked out by using arguments, writing mini-stories, do simple experiments, and solve problems involving "formulas" and definitions of their own design. Finally, in some cases the stage of generalization can be reached. Here we want to see some of the students go beyond the data and the story and find diverse connections. They might look for the solution of a special problem, do an experiment of their own and design or write another story that goes beyond the main story. I cannot think of a better way to motivate students to become creatively involved in reshaping their prescientific concepts.

2. The second question is concerned with the fact that science is, to a great extent, the story of problem solving, accompanied by repeated failures rather than a succession of aha-experiences of sudden insight. How would one incorporate "repeated failures" in science stories? As I have said earlier, science, of course, is more than a collection of aha-experiences - it cannot be reduced to a series of dramatic insights. We must show students that scientific work is difficult and arduous, and mostly a collective effort. For example, when we discuss Newton's laws of motion we must go beyond the textbook and tell the story of the struggle to pin down the diverse phenomena in a small set of laws. Of course, we must also pay tribute to the collective effort of scientists whose names are not well known. One of the best science stories my students have designed is entitled "A day in the life of Robert Hooke, FRS". Why not a science story: "A day in the life of John Bonelli, Ph.D.?"

3. The third question has to do with native science and women's contribution to science. How can we utilize native science? How can we emphasize more women's contributions to science? Only recently have we started to recognize, respect, and build on students' preconceptions of science. I am not well acquainted with oral stories of the native people of New Zealand, or for that matter with those of native people of Canada. However, they must have had stories about the creation of the world, about the motion of the stars, about fire and heat. We could, for example, discuss the constructive and destructive potentials of heat in the form of nuclear power - and connect to an appropriate story that remembers the eruption of a volcano. We all have intuitive understanding of what heat is and how it transfers. There are stories among the natives that touch on these things.

As far as telling stories involving women scientists is concerned we should look at the collective effort of scientists where women were crucially involved but somehow lost out in the final credits. There are many examples in physics, chemistry and biology, but one of the best is the work of Rosalyn Franklin who supplied the crystallographic evidence for the structure of the DNA molecule. The splendid British BBC made for TV movie The Race for the Double Helix (filmed in Cambridge where the discovery took place) should be shown in every secondary biology and physics class. And why not a science story entitled "A day in the life of Mary Bronski, Ph.D."?

4. The last question I wish to consider is perhaps the most difficult to answer. It was argued at the seminar that science stories are fundamentally different from stories in the humanities. This is so, it was explained, because in the sciences "the moral drives the story" and in the humanities "the story drives the moral". In other words, the outcome of the science story is determined by the underlying demands of the methodology of the science, and therefore inevitable, whereas the outcome of the story in the humanities is determined by the story writer, and therefore is not inevitable. For example, when we tell the story of Newton's discovery of gravity, no matter how exciting the story seems to be, the outcome is fixed, therefore diminishing the dramatic impact of the story. On the other hand, the story of Hamlet is always exciting even if the outcome is known. This is so because the psychological forces at play are open to interpretation by the director, the actor and audience. The character of Hamlet then can have several interpretations, and indeed each generation reexamines the implications of the drama. Does not a predictable outcome diminish the motivational value as well as the dramatic effect of the science story?

Thomas Kuhn understood the problem of teaching science in historical context. He pointed out that it is especially difficult to impart a sense of history to science students because "science students 'know' the right answers" (Kuhn, 1962). Thus it is useless to examine Galileo's inclined plane experiment, after a standard textbook rendition of constant acceleration has been given. I would like to argue that the teachable moment of the historical context in science is at the early and middle school level and maybe again in graduate school. However, let me briefly look at the question of a predictable outcome diminishing the dramatic effect of a science story.

I will look at only one science story (probably the paradigmatic one, at least in physics) that my students have developed. I could have, of course, chosen stories from biology and chemistry that would make the point just as forcefully.

Textbooks invariably tell students that Galileo made measurements without initial hypotheses and tabulated the results of distance versus time roughly the way textbook experiments of "verification" do, following the "scientific method". Of course, this is boring and is historically wrong. Galileo investigated the consequences of no less than four hypotheses. He reasoned on the basis of logic, physical possibility and simplicity, often by way of thought experiments. He found that thought experiments (as students also do) are far more compelling than experimental evidence. For example, he found by mathematical argument alone that two of his hypotheses were equivalent, although only one was easily testable experimentally. Another hypothesis predicted a result which was seen to be absurd. However, students should be invited to discuss "physically absurd" results. Are tachyons physically absurd?

Finally, Galileo made the imaginative leap of "diluting" gravity along the inclined plane and neglecting the effect of friction.

# Chapter 9

## Conceptual Change, Historical Context, and Science Stories

(See Stinner and Williams, 1993, published in *Interchange*, Vol. 24, 87-104.

### Introduction

The purpose of research in applied fields is to inform practice. In an ideal world the findings of university researchers in science education would guide the practice of teaching science. Unfortunately, we do not live in an ideal world and the teaching of science, more often than not, is based on a combination of educational folklore and teacher experience.

It is ironic that although science teachers know about science research they do not look more to research for guidance in their practice. But anyone who has taught school science knows that in the midst of a science lesson there is little time to reflect on research findings, much less on philosophical issues relating to science education. Under the pressures of classroom teaching, planning lessons for five or six different classes per day, some of which may not be in science at all, science teachers tend to be pragmatists, interested in what will work in their classroom tomorrow. Accordingly, if that ideal world in which research findings of university science educators inform the practice of science teachers is to be achieved, science educators must present their findings to the field in ways that encourage implementation by teachers.

A case in point is the simmering controversy within the constructivist camp between supporters of Piagetian theory and adherents to the alternative conceptual frameworks (ACF) viewpoint. Piagetian theory has been under attack for some years by supporters of the notion that firmly held ACF's derived from everyday experience impede science learning.

The constructivist perspective holds that we quite literally construct our own world from our personal experience, making sense out of new experience through the lens of our existing conceptual structures. Glaserfeld (1989) uses the term "transduction" to describe the processing of sensations into the conceptual structures that constitute one's personal knowledge. The constructivist paradigm contains two possible sources of difficulty in interpreting new experience. One based on a Piagetian theory points to inadequate mechanisms of "transduction"; the other based on an ACF theory points to already held ACF's derived from everyday experience getting in the way of acceptance of "correct" concepts.

**The Piagetian Perspective**

Piaget posits cognitive instruments which he terms operational schemata that the learner uses to make sense out of experience. Operational schemata are context independent and develop through a process of accommodation and assimilation. In Piagetian theory, cognitive development is the development of increasingly powerful operational schemata through these two processes. Garrison and Bentley (1990) bring the issue into philosophical focus by comparing Piaget's notion of assimilation to Kuhn's "normal science" and accommodation to his "revolutionary" science. This is a rather neat philosophical analogy but one which would do little to enlighten the "average" secondary science teacher, much less an elementary school teacher of science.

According to Piagetian theory, lack of understanding of experimental processes such as identifying and controlling variables and conceptualizations such as density and buoyancy result from poorly developed operational schemata. Hence Piaget's theory is concerned with process of transduction itself rather than the conceptual structures that result from transduction.

Typically, Piaget's concrete operational subjects were unable to apply a common explanation to a set of related phenomena in his clinical interviews. For example, after stating the principle of buoyancy, concrete operational subjects would use various explanations when explaining specific examples of objects sinking or floating. The following are excerpts from a Piagetian interview we videotaped some years ago of a Grade 11 student with a B average in chemistry on the topic of buoyancy.

Interviewer: You have placed these objects in the pile of floaters. Why will they float while these other objects will not?

Subject: These objects are more dense than water so they will sink but these others are less dense so they will float?

Interviewer: Alright, lets try them.

Some of the explanations for floating during the subsequent trials included "has air holes" "plastic floats, I don't know why", "it's made of wood and wood floats", and "the water is heavier" but could not elaborate. For sinking objects: "iron sinks", "no air holes", "the washer has a hole in the middle", "surface tension holds it up and it sank because you broke the pressure" and a variety of vague statements about air and water pressure.

It does not appear that preconceptions interfered with comprehension. Rather, the subject was unable to apply a consistent explanation to the various examples and saw no need to do so. While Piaget was loathe to suggest interventions to promote cognitive development in such cases a reasonable approach seems to be to provide unspecified learning experiences requiring lots of accommodation and assimilation.

**The ACF Perspective**

Linn (1982) criticizes Piaget's theory as under-valuing the role of prior knowledge in understanding science and focusing excessively on content-free strategies. She cites a plethora of studies, many her own, supporting the importance of factual knowledge in reasoning. These studies are strengthened by common-sense and the experience of high school teachers across North America. It would, indeed, be difficult for a high school chemistry student to reason logically about stoichiometry without a pretty thorough understanding of the mole concept. On the other hand, even an inexperienced cook with a moderate ability to reason about proportionality could scale down (or up) a recipe for corn bread. Clearly, the former case requires a significant amount of domain-specific knowledge while the latter requires little more than a reasonably well-developed operational schemata for proportional reasoning. A common stratagem used by chemistry teachers when teaching stoichiometry is to teach first for understanding. However, this means decontextualizing problem solving, then, when that fails (as it inevitably does with some students) to teach algorithms for standard problems to enable the student to pass the next examination.

Garrison and Bentley (1990), support the ACF position on philosophical grounds. Drawing an analogy between an ACF and a current science paradigm they suggest that students have difficulty accepting new conceptualizations in the face of a firmly embedded set of highly verified conceptualizations derived from everyday concrete experience. The ACF prescription would be to challenge these ACF's in various ways.

**The Classroom Teacher's Perspective**

What is a science teacher to do when confronted by complex arguments and seemingly contradictory theories put forth by learned researchers? Clearly, if research is to have any influence on practice, it must be presented to the science teacher in a form that is meaningful and usable.

Large context problems (LCP's) as proposed by one of us (Stinner) are an instructional strategy that addresses both points of view. Appropriately designed LCP's are inherently more interesting than the contrived problem exercises found in most text books. They require the learner to integrate knowledge and ideas from a variety of sources and LCP's can be worked on in groups. The latter is of great benefit because cognitive conflict resulting from the social interaction among peers is much less threatening than when created by interaction with a teacher. A further advantage of LCP's is that they do not readily yield to the application of algorithms.**The large context problem**

The LCP approach was originally developed as a response to the discovery that learning could be well motivated by a context with one unifying central idea capable of capturing the imagination of the student (Stinner, 1980, 1981, 1989). For each given major topic in physics , such as kinematics, several LCP's for the teaching of high school physics were developed. The student then chooses one LCP that attracts him/her. However, each LCP had to be so designed that all of the physics for a particular topic is used for the successful completion of the problems suggested by the context. What is so attractive about this kind of setting is that the problems are generated naturally by the context and will include problems that are artificially given out of context in a textbook for a given topic. Moreover, students' responses to the LCP approach suggest that they should be designed by the instructor. Indeed, ideally, LCP's should be designed cooperatively by students and the instructor. This also gives the instructor the status of researcher and the student the feeling of participation in an on-going research program.

Teachers, of course, have used such approaches in the past. The design of simple mechanical contrivances to perform some task would be one kind of large context problem. Tinker toys or erector sets are an excellent medium for doing large context problems. The mechano sets of the post-war period and legos used by today's children are well suited for creating LCP's for a children. These settings then become the student's first significant and organized "hooking on to an aspect of the world of his/her choosing" (Stinner, 1989), in what Whitehead (1967) calls the stage of romance. This stage provides the setting for problem solving, or what Whitehead calls the stage of precision.

The LCP approach requires the learner to integrate knowledge and ideas from a variety of sources. One of the principles that should guide us in designing LCP's is that "cognitive strategies will be most effectively developed if students are exposed to a variety of novel problems...in contexts which are as close to eventual transfer situations as possible...(Allen and Whyte, 1980). di Sessa (1988) and Driver (1989) argue that children do not have organized theories about the world, but possess a large number of fragments. Transition to scientific theories then involves the systematic organization of these fragments. Driver recommends that provision be made for students to receive a "range of experiences within a domain and to support and encourage the systematic and coherent organization of students' interpretation of those experiences" (Driver, 1989).

We have found that students regard appropriately designed LCP's more interesting and motivating than the contrived problem exercises found in most text books.

Our experience suggests that the immediate benefit of contextual problem solving (carried out concurrently with, or right after, conventional classroom teaching) is that it enlarges the student's understanding of basic laws and principles. In addition, the student often goes beyond just the successful mastery of the problem situations. For example, for the study of kinematics, if the student chose, say "Physics and the Bionic Man", he/she investigated the current research in the physics of bionic parts; or if the student chose "Physics on the Moon", he/she investigated the physics of moon architecture and the general problem of adaptation to low-gravity environment (Stinner, 1989). In this manner the LCP approach provides a vehicle for traversing what Whitehead (1967) refers to "the path from romance to precision to generalization".

**Historical setting as a vehicle for conceptual change**

There is a growing sense among many researchers in science education that one sees "tantalizing parallels between intuitive conceptions in certain domains, e.g., mechanics electricity, astronomy, and historical prescientific conceptions" (Nercessian, 1989). Granted, we cannot expect students to recapitulate high-grade scientific thinking of the Aristotelian or the Galilean variety. However, we can make a plausible case for an essential recapitulation for domains that are familiar to the student. Driver and Easley, reported that students' views often "reflect analogies with historically held views" (Driver and Easley, 1978).

Many researches claim that students have "Aristotelian" ideas about the relationship between force and motion, and demonstrate "medieval" understanding of motion that is akin to the concept of impetus (di Sessa, 1982, Viennot, 1979, Driver, 1985, p. 88). Even in areas that are further removed from everyday experiences, such as electricity, researchers claim that students seem to have an intuitive understanding of electric fluid, not unlike that held by the electricians of the late 18th century (Shipstone, 1989). Of course, students do not have Aristotle's clear understanding of the difference between violent and natural forces (what we today call contact forces and action-at-a-distance forces). Nor do students have a notion of impetus that even resembles the complexity of the concept in the context of medieval physics.

It follows then that students are unlikely to have private theories that suggest an understanding of inertia, for example, as first realized by Galileo and later propounded by Newton. Nor do they show ideas that would lead them to the charge theory of electricity, as propounded by physicists in the first half of the nineteenth century. It seems that students preconceptions, which are based on everyday experiences, do not prepare them for such abstract and refined concepts as inertia or electric charge. There is little doubt that learners actively construct ideas about phenomena around them. However, " this does not necessarily indicate that a learner has, for example, any kind of theory of 'naturalistic' physics" (Kenealy, 1989, p. 210.) Driver makes a similar point quite strongly:

> *Learning science, therefore, is seen to involve more than the individual making sense of his or her personal experiences but also being initiated into the "ways of seeing " which have been established and found to be fruitful by the scientific community.*
>
> *Such 'ways of seeing' cannot be 'discovered' by the learner - and if a learner happens upon the consensual viewpoint of the scientific community he or she would be unaware of the status of the idea" (Driver, 1989).*

According to Garrison and Bentley (1989) neither the ACF advocates of domain-specific theories nor Piagetian global theories of developmental psychology entirely account for the difficulties students have in accommodating high-level concepts such as inertia. What seems to be involved in the accommodation of a concept like Newtonian concept of inertia is a complete "breaking with everyday experience" (Garrison and Bentley, 1989).

Duschl and Hamilton (1990) investigate the consequences of the assumption that the "process of theory development by scientists can be compared to an individual's acquisition of knowledge of the world". Their concern seems to be the need for a clear differentiation between the contexts of justification and the context discovery. They argue that a problem arises when a choice must be made between presenting a theory in a classroom in the historical context of justification mode or in the historical context of discovery mode. The distinction between these two contexts would suggest that we use the first whenever we talk about normal science and the second whenever we talk about revolutionary science. This usage would then correspond respectively to weak restructuring, or what Piaget calls assimilation, and to radical restructuring, or what Piaget call accommodation. However, we make the initial assumption that in most historically-based science stories we will develop, radical restructuring, or accommodation on the part of the student will take place. We wish to argue that this kind of conversion, or Gestalt switch can best be accomplished by contextual teaching in a historical setting.

Another good reason for teaching science in historical context is given by Novak. He argues that the meaning of a concept is strengthened and defined by the "network of propositions the learner has connected to it" (Novak, 1977). In this statement we interpret Novak to say that concepts, such as electron, for example, are fully understood only if in the mind of the learner the concept is diversely connected (electricity, chemistry, atomic theory, etc.). Our hypothesis is that diverse connections that enrich conceptualization can effectively be established in a multidisciplinary context that attracts the student and is historically well placed. This latter claim can be regarded as the criterion whereby we would differentiate between bona fide concepts and theories in science, and 'children's theories', "having a coherent internal structure and being used consistently in different contexts" (Driver, 1989).

Finally, both the ACF advocates and Piagetians recognize the value of studying case histories in science. These historical studies are thought to provide new insight for science educators about concept formation. We will discuss the requirements of the historically placed science story, after briefly summarizing attempts to introduce a "story-line" to science teaching in general.

**The "story-line" approach to the teaching of science**

As early as 1947 J.B. Conant introduced his Understanding Science: An Historical Approach, followed by the splendid series (and still fresh) Harvard Case Histories (Conant, 1957). At about the same time

Gerald Holton made a credible attempt to integrate the history of science in his otherwise conventional treatment of university undergraduate physics in his Foundations of Modern Physical Science (1957). These historical approaches have been and continue to be successful in the hands of a few teachers who see relevance in imparting historical knowledge to students (Arons, 1988). Even the writers of the highly academic PSSC Physics series attempted to thread the theme of particle-wave duality of nature as a "story line", however contrived, throughout the presentation. A few years later the Harvard Project Physics series (1967), under the leadership of Gerald Holton and Fletcher Watson, introduced a history-based textbook series. This series also uses "story-lines" based on such themes as wave-matter duality, entropy, and mass-energy equivalence, and on controversies such as those between Leibniz and Descartes, Newton and Huygens, and Copernicus and Ptolemy. This series was, by consensus, a "glorious failure" to replace the conventional physics texts. Many physics instructors, however, still use these books as their most trusted reference for historical context and ideas for imaginative teaching.

Several writers and science education researchers have recently again recommended and have elaborated the notion of using a "story line" approach to the teaching of science. Arons (1989) believes the best way to attract students' attention as well as organize a science course is by way of a "story line". He outlines in some detail the historical settings of important discoveries and events. Arons is referring to what are essentially good science stories that have intrinsic interest and show connections not to be found in textbooks. These stories seem to be excellent small versions of Conant's case histories "that can be infused into introductory courses, without seriously affecting the amount of physics being covered" (Arons, 1989).

Michael Ruse has designed a large-scale case study based on the controversy between creationism and the theory of evolution. He uses this study to set a large context with one unifying central idea that attracts the imagination of students. He says: "rather than simply going straight at students with such worthy (but boring) standard topics as criteria of confirmation, conditions for adequate explanation, and the like- at least, rather than going at students abstract isolation- one does better to plunge into actual areas of science, from which the pertinent philosophical messages can be extracted" (Ruse, 1989). In other words, he set a LCP that generates the major ideas and problems of the philosophy of science naturally. The last requirement of a well-placed LCP, namely that the context be designed by the instructor, was also fulfilled.

Jutta Luhl, a German science teacher, has developed a "story-line" approach to teach atomic theory in Middle Schools. Rather than "teach the Bohr model of the atom at a very mechanical level", she has developed a mini-course that traces the development of the idea of atom from the Ionians to Dalton (Luhl, 1990). Like Ruse, Luhl set a large context in which one central idea that attracts the imagination of the student the important connections that lead up to the Bohr atom are explored. These include an understanding of the historical evolution of the idea of the atom, including basic principles, such as the conservation of mass and energy and the law of definite proportions. This approach may be more time-consuming then the conventional textbook approach. However, the understanding of the student as well as the quality of interaction between the student and the teacher is lifted from an ordinary to a high-grade level.

Kieren Egan has argued against the dominant objectives-based procedures of curriculum planning and recommended a procedure based on the story form. His argument is that the story metaphor is more appropriate in describing what we learn about the world, according to research based on "constructivist nature of human sense making" (Egan, 1986).

Wandersee has been using Egan's Story Form in developing what he calls Historical Vignettes to enhance the teaching of science to young students. He uses "carefully chosen examples from the history of science...tailored to the interests of the science students..,"(Wandersee, 1990). We will use some of Egan's ideas of planning a story in general for designing "science stories" in historical contexts.

In seems that all of these writers to a lesser or greater extent recommend a "story-line" organization of a science topic that resembles our original LCP approach. In summary, the central features are based on the following recommendations:

1. Map out a context with one unifying central idea that is deemed important in science and is likely to capture the imagination of the child.

2. Provide the child with experiences that can be related to his/her everyday world as well as being simply and effectively explained by scientists' science, but at a level that "makes sense" to the student. (If ideas and concepts are introduced too early, the child may not be intellectually ready; if introduced too late the child's science may be ossified into layman's science: the child will, have lost interest (Osborne et al, 1983)).

3. Invent a "story line" that will dramatize and highlight the main idea. Even though the main idea or ideas are should be placed correctly in history the story may or may not be historically correct (remember Galileo and the Leaning Tower of Pisa story!) Egan's recommendation that one should identify an important event associated with a person and find binary opposites, or conflicting characters or events may be appropriate here.

4. Ensure that the major ideas, concepts and problems of the topic are generated by the context naturally; that it will include those the student would learn piece-meal in a conventional textbook approach.

5. Secure the path from romance-precision- generalization. This is best accomplished by showing the student that

a. problem situations come out of the context and are intrinsically interesting,

b. that concepts are diversely connected, within the setting of the story as well as with present-day science and technology.

c. there is room for individual extension and generalization of ideas, problems and conclusions.

6. Ideally, the science story should be designed by the instructor, in cooperation with students, where he/she assumes the role of the research-leader and the student becomes part of an on-going research program.

These six features then will comprise our revised LCP, that we now call "science story". Telling a coherent story, with a beginning, a middle, and a provisional end, may be the best way for learning, remembering and re-telling of ideas (Kenealy, !989, Miller, 1988). Kenealy reminds us that "In fact, most people will impose coherence on a set of random sentences in an attempt to create a context for what they are reading or hearing (Kenealy, 1989).

Our ultimate aim should be to introduce children to science, much the same way as they have been "inducted into full membership of their culture" (Egan, 1988). We would like to take up the challenge contained in the plausible suggestion "that the role of the story or the shaping narrative is becoming increasingly recognized in all subject areas, even in the sciences, which had once seen themselves as positivistically immune from subjective shaping" (Egan, 1988).

The following is a brief summary of a course that we introduced at the university of Manitoba. In this program we attempt to teach student-teachers the craft of designing a "story-line" which is oriented toward elementary and junior high school science teaching. We will now turn to discuss briefly the content and pedagogy of teaching this craft to fledgling science teachers

**Write your own science story: Teaching the history of science to student teachers**

We are offering a course (senior elective) at the university of Manitoba that looks at the development of science education in terms of the major achievements of science as well as the practices of scientists throughout history. From these achievements and practices students are asked to draw materials to develop hands-on teaching contexts, namely "science stories". These must be designed according to our discussion above, to be used in the elementary or junior high school science classroom. The science stories are then presented to class for a critical examination (essentially a peer review). Students design four "science stories", one for each of the major historical epochs (see below). These "science stories" are now being edited and will be used in the class room.

**I. The Ionians, and the Greeks (From Thales to Ptolemy).**

The science of the Greeks, because it is essentially high-grade thinking based on unaided observation, seems especially well suited for teaching elementary school and junior high school science.

In fact, one can argue that the "teachable moment" of the historical context in science is precisely at this time (10-14 years) and perhaps again in graduate school. It may be critical at what age we introduce experiments and ideas in science. If we introduce them too early we will encounter problems because intellectually students are not ready. If we introduce them too late "children's science can ossify into layman's science,...showing little or no motivation to change their present view (Osborne et al). Science teachers in high school know that it is very difficult to teach science in historical context because students, as Kuhn has pointed out, "know what all the answers are" (Kuhn, 1962). (see feature No 2. above)

The following are examples of topics related to the science of the Ionians and the Greeks that can be developed into teaching units based on the idea of “science stories”:

Archimedes' law of the levers, his law of flotation and his law of reflection involve elementary science concepts that are best taught in historical context.

The three laws of physics (reputedly discovered by Archimedes) that have essentially remained unchanged: law of the lever, law of flotation, and the law of reflection.

Archimedes' mathematics, as it applied to his physics. Archimedes' screw, and

Archimedes: physics and war machines.

Determination of the length of the year and the circumference of the earth: Aristarchus, Eratosthenes.

Plato's cosmological question: "By the assumption of what uniform and ordered motions can the apparent motions of the planets be accounted for?

Plato's theories about the origin of the universe

Zeno's paradoxes.

The experiments of Empedocles; for example, "the water clock experiment", his experiments in optics to test his theories.

Democritus' atomic theory of matter.

The three outstanding mathematical problems of the Greeks: the squaring of the circle, the trisecting the angle, and the Delian problem.

Hippocrates and medical science.

Aristotle's biological studies, his physics and his great experiment: "The embryology of the chick".

he Ptolemaic solar system.

Hero's experiments.

## 2. Later Middle Ages to Copernicus

Young science students are especially well predisposed to consider some of the main scientific concepts as put forth by the natural philosophers of the middle ages. The notions of impetus and mean value in physics and the application of a simple atomic theory in chemistry are examples of concepts that lend themselves to profitable classroom discussion.

The following are examples of topics related to the science of the middle ages that can be developed into teaching units, based on "science stories":

The concept of impetus in the teaching of motion.

The application of the mean value theorem to problems involving average value.

The optical experiments of Theodoric of Freibourg, especially the experiment to discover the "Causes of the Rainbow".

"A day in the life of an alchemist."

Roger Bacon's philosophy of scientific method.

Medieval optics and theory of light

Could medieval physicists have developed a telescope?

Roger Bacon (13th century), the "new scientific attitude" and the nature of scientific enquiry.

Thomas Aquinus' attempt to reconcile the scriptures with the physics of Aristotle.

Robert Grosseteste and scientific enquiry. His discussion of the inductive process deals with the passage from observation to laws anticipates the 17th century scientists' understanding of scientific method.

Nicolas Oresme anticipated much of Galileo' work on motion.

## 3. From Copernicus to Newton: The Scientific Revolution.

Most of the scientific developments and concepts of the Renaissance (Copernicus' geocentric model of planetary motion, Harvey's circulation of the blood) as well as those of the scientific revolution proper ( Galileo's inclined plane and pendulum experiments, Torricelli's measurements of barometric pressure, Boyle's experiment, Hooke's law) are teachable to young students (10-14 years).

The following are examples of topics related to the science of the Renaissance and the seventeenth century that can be developed into teaching units, namely "science stories":

Copernicus and the geocentric solar system.

The problem of navigation in the 15th and 16th centuries.

The Julien calendar: why reform was necessary.

The problem of finding the longitude at sea.

Observations of the sky for children.

The compass and how it changed navigation.

Mercator and the problem of representing the spherical earth upon a plane map for the purpose of navigation.

The development of the theodolite and triangulation for determining distances.

Leonardo da Vinci's mechanical inventions.

Vesalius and the study of anatomy and physiology.

Chemistry in the 15th and 16th centuries.

Galileo's inclined plane experiment.

Galileo' telescope.

Robert Hooke and the microscope.

A day in the life of Robert Hook, FRS.

Galileo' astronomical observations.

Newton's mechanical experiments.

Newton's optical experiments.

Harvey's theory of the circulation of the blood.

Roemer's determination of the speed of light.

Kepler's "War on Mars".

**4. From Newton to Einstein: The Modern Period**.

Many of the main ideas and concepts in biology, chemistry and physics of the 18th and the first half of the 19th century can be discussed in early science education and many of the key experiments replicated. The story of Lavoisier and the chemical revolution and Dalton atomic theory is appropriate for elementary and junior high school science. Faraday's electromagnetic experiments are easily performed using simple materials. In biology teachers should develop simplified approaches to show how Pasteur's experiments refuted spontaneous generation and how Semmelweiss' observation led to the germ-theory of disease. Most of the experiments involved in Faraday's work on electricity and those in Joule's work in establishing the principle of the conservation of energy are easily replicated and the relevant concepts amenable to elementary analysis. We should probably do better here than what conventional textbooks would allow us to achieve.

Pasteur's method of "disproving" spontaneous generation is still considered the textbook case of controlled experimentation in biology. Moreover, his experiments that laid the foundations of the germ theory of disease can be understood and replicated by young students. Textbooks in general miss the opportunity to create the appropriate excitement in showing how to replicate them.

The following are examples of topics related to the science of the 18th and the 19th centuries, that can be developed into teaching units based on "science stories".

The phlogiston theory in chemistry.

The confrontation between Priestly and Lavoisier over oxygen.

Lavoisier's experiments to investigate oxygen.

Volta's experiments with electric batteries.

Dalton's assumptions, his observations and his experiments which led to his atomic theory of matter.

Davy's experiment separating water by an electric current.

Chemical shorthand: from the alchemists to Dalton and then to Berzelius

Faraday's electromagnetic experiments.

Young's experiments to demonstrate the wave nature of light.

Making a simple spectroscope.

Determining the distance between two point by triangulation.

Determining the distance to a star by the parallax method.

An account and a discussion of Darwin's The Voyage of the Beagle as a background to his theory of evolution.

A discussion and partial replication of Pasteur's experiments to put to rest spontaneous generation.

The evidence for the germ-theory of disease.

The story of the unit charge in electric phenomena: from Coulomb's measurements, to

Faraday's electrochemical experiment

to Thompson's discovery of the electron. Do electrons really exist?

John Tyndall and the Tyndall Effect.

Faraday's lecture on "A Burning Candle".

Laplace' theory of the origin of the universe.

Linnaeus' classification: an improvement over Aristotle's?

The Doppler effect and its use in astronomy.

The discovery of Neptune: Newton again vindicated.

Chemistry, Physics and the discovery of photography.

Our aim is to extend this program and reach into the 20. century. We want to set up contemporary contexts that make connections with the past by way of those "science stories" that the student is already acquainted with.

**Summary and Conclusion**

ACF researchers interpret their findings to mean that students are reluctant to give up their views about the world because of the utility such views provide. These researchers argue that conventional formal (expository) instruction is unlikely to permanently change students' views. In fact, pre-scientific views seem to persist even after students receive good marks on putative problem solving tests. This strongly suggests that students are being taught concepts primarily by way of algorithm-recitation techniques.

On the other hand, a Piagetian interpretation of the same data implies deficiencies in the development of students' cognitive structures. A Piagetian prescription would be to challenge the student with experiences that create disequilibration that requires accommodation and assimilation. The aim of these experiences would be to produce cognitive development.

We argued that even if the clarification of the epistemology of concept formation in science were possible it alone would not provide us with clear implications for the teaching of concepts. However, AFC advocates as well as Piageans, would agree that understanding in science requires non-mechanical approaches that appeal to the imagination and involve such procedures as analogy, limiting case analysis, thought experiments, and especially on-going discussion.

Conceptual change, of course, has always been a learning process for the scientist as well. While it is manifestly clear that we cannot expect the learning process to simply recapitulate the historical process, we believe that we should be able to foster a good understanding of history and in a limited sense (as in the case of elementary kinematics and dynamics) recapitulate the historical development.

Therefore, we have argued, a sound understanding of science must include historical context. The contexts of discovery and justification must be given in order to provide appropriate evidence of true comprehension of science, both as a process and as a product.

To teach science in a historical context we require teachers who have more than a cursory acquaintance with science history and who know the basic findings of the philosophy of science. In addition, we maintained, science teachers will be more effective if they teach by way of science stories (large context problems) that are connected to the history of science and provide appropriate evidence for the formation of concepts. In order to do that, we stressed that science teachers must be able to develop their own science stories and show facility in using them in a classroom. Moreover, we have described how we developed a course for senior students in science education that surveys the development of the major scientific ideas from the Ionian physicists to the present. One of the tasks in this course is for science education students to develop science stories for the main scientific epochs. These are then presented in workshop format, extensively discussed and criticized by other student teachers. Ultimately these science stories will be used in the classroom to provide appropriate evidence toward conceptualization that appears to the student to be intelligible, plausible and fruitful.

We are claiming that the instructional strategy of contextual teaching by way of "science stories" addresses both the ACF and the Piagetian points of view. Moreover, it appears that historically-based science stories might be one important way to bring about accommodation, or radical restructuring. This seems reasonable because the context of discovery is stressed naturally when developing science stories. We are looking for further testing, in actual classroom application, of our original hypothesis that diverse connections that enrich conceptualization can effectively be established in a multidisciplinary context that attracts the student and is historically well placed.

Ultimately one would like to see a two to three year program (10-14 years of age) that guides the student through historical contexts starting from the Ionians to the present. The science stories should be grouped in such a way that no matter which one the student picks from a given cluster, the content and processes covered will match those in the prescribed curriculum. However, practicality may demand placing the students into manageable groups of 3 to 4, while working on 3 to 4 different science stories.

Let us take, for example, the three laws of physics that the Greeks discovered (see above). To attract the interest of all students, one could easily develop quite different settings and dramatizations (this was successfully done by the student teachers). Teachers then could capitalize on having students discuss these contexts both formally and informally, thus offering different points of view. Problems which arise naturally from the contexts then can be presented by the students. The diversity offered by the different story-settings would then enrich the students' background knowledge as well as stir further interest.

Ultimately one can envisage science being taught by way of historically based contexts from elementary grades right up to high school. In an ideal world, contextual teaching based on a "story line" could go on until specialization would seem to be inevitable. In such a world, textbooks would have to be rewritten and their role reconsidered.

In the real world, however, textbook-centered teaching appears to serve mainly those well who are already committed to science, namely our future "normal scientists" (Aufshnaiter, 1989). It seems plausible that textbook science discriminates against the highly gifted as well as the student in search of general scientific understanding (von Baeyer, 1990). As Kuhn (1962) pointed out, textbook science alone is unlikely to produce the scientist "who will easily discover a fresh approach", or, we may add, educate the layperson who will be scientifically literate. To achieve such a goal, science teachers must recognize the motivating potential as well as the pedagogic superiority of science stories, appropriately placed in historical context.

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# Chapter 10

## The philosophies of Science and Science Education

### The central problems of scientific inquiry

Let us take a closer look at the central problem of the philosophy of science As we have already discussed philosophers of science deal with the nature of scientific inquiry. The central problems they consider are arguably the <u>problem of induction</u> and the <u>problem of explanation</u>. Let us look at these problems in an effort to show how they have generated the main questions that major schools of thought of the philosophy of science are still attempting to answer.

### The problem of induction in science

The question of induction in science is: "What sort of reasoning is it that allows us to make generalizations that are more comprehensive than the facts on which they are based?" (The word *generalization* can be seen as *theory*, like Newton's theory of gravitation.)

Inductive reasoning, expressed on the model of deductive logic is typically of this form: "This X is a Y, and that X is a Y", etc., leading to an unrestricted general statement for a conclusion that " All X's are Y's". According to the principles of deductive reasoning, however, arguments of this form are invalid. They are invalid for two reasons. First, the general conclusion is supposed to apply universally, based only on a finite collection of premises. Secondly, we can never be certain of the truth of the conclusion since a case may always turn up to falsify the conclusion.

Let us illustrate what we have said with simple examples. If we assume that the premises are true and we say:

All men are mortal.

Einstein is a man.

Therefore, he is mortal.

We accept this conclusion as valid. But suppose we say:

If light bends S seconds of arc when passing the sun then Einstein's theory of general relativity must be true.

It is the case that when light passes the sun it bends S seconds of arc.

Therefore, Einstein's theory of general relativity is true. In this case our conclusion may not be true.

Let us represent these arguments (called syllogisms in logic) symbolically. They look like this:

| 1. if X then Y | 2. If X then Y |
| --- | --- |
| X | Y |
| --------------------- | ----------------- |
| Therefore Y | Therefore X or not X |

The second statement is the reasoning known as the "Fallacy of the Affirmation of the Consequent". Judged on the deduction model, then, induction is unreliable, both as a discovery procedure, as well as a justification procedure. However, it is tacitly assumed that demonstration of all scientific generalizations, such as the law of free-fall, must follow the deductive model. Harre responds to this by saying that "we are faced with a condition of continuing uncertainty in the sciences that is at variance with the confidence that scientists feel in their conclusions" (Harre, 1971)

Scientists, indeed, seem to ignore what logic says and generalize from a limited set of data all the time. Here are examples of "scientific reasoning":

1. Whenever we heat metals they expand.

Therefore, we conclude that 'all metals, when heated, expand'.

2. Galileo made certain measurements relating to the motion of a metallic sphere along an inclined plane. Based on a few "tries" he generalized to the law of free fall (distance covered by a freely falling body is proportional the square of the elapsed time).

3. Newton attempted to "explain" three classes of apparently unconnected phenomena: the motion of the pendulum, the phenomenon of the tides, and the elliptical orbits of the planets. He found that to accomplish that he needed only four laws, three laws of motion and the inverse force law of gravitational attraction.

4. Spectroscopic measurements on earth suggested that an element, with an atomic mass between Hydrogen and Lithium, should exist. This element (Helium) was later "discovered" in the sun before it was found on earth.

All of these examples are connected with the central problem of induction. Over 200 years ago the English philosopher David Hume showed us that induction cannot be justified. He argued that only deductive or demonstrative arguments, like those in geometry, lead to certain conclusions from self-evident premises. Inductive or generalizing arguments, proceed neither from self-evident premises nor do they lead to certain conclusions. So he concluded that scientific knowledge is suspect. In connection with the problem of induction the 20th century mathematician and philosopher, Alfred North Whitehead was led to remark that "science went right ahead, not knowing that Hume had refuted it".

It seems that what scientists do is generalize inductively and then argue deductively (refer to deductive reasoning in previous chapter) from these generalizations to specific instances with confidence (See fig ). What is puzzling here is that

a. often a generalization can be arrived at from a very few instances, and

b. further multiplication of instances does not seem to strengthen the commitment to the generalization.

In the examples of scientific induction above we arrive at a generalization very quickly in the first case. Even in the second case Galileo required very few "runs", although it took him a long time to work out the consequences of his hypotheses. In the third case again very few measurements were required by Newton, but a considerable amount of difficult mental effort and time was involved. In the last case we have a complex story of scientific detective work that spans the time from about 1820 to the 1890 (see fig. )

In each of the generalizations above we decided that human imagination was able to find generalizations from which it is possible to make deductive inferences, in some sense of deductive. For example, from Newton's laws we are able to "deduce" the periodic motion of a pendulum as well as the elliptical motion of the planets. From the theoretical framework of atomic theory and spectroscopy we can "deduce" that the outer atmosphere of the sun contains helium.

**An attempt to solve the problem of induction: Popper**

The most famous contemporary philosopher of science is arguably Sir Karl Popper (b. 1902). He wanted to solve the problem of induction in science in a novel way. He maintained that neither animals nor men use induction to solve problems in their environment. This is so because there must always be a framework of expectation, and, as we have seen, repetition of instances cannot confirm a generalization. We saw at the beginning of this chapter that a generalization admits to consequences that can be shown to be false. Popper even argued that true and false theories have equal probabilistic status! However, Popper thinks that there is a way out of the dilemma we are facing. If a theory or hypothesis fails to survive a test we can reject that theory or hypothesis. Therefore we must construct scientific theories by the method of eliminating false ones. The task of science, then, is to imaginatively invent theories of a high degree of falsifiability. In fact rational thinking itself for Popper consists in detecting errors, in eliminating them, and in learning from them. The type of argument Popper is offering, according to formal logic looks like this:

if H then C

Not C

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Therefore not H

As far as scientific processes resemble formal logic Popper's method of falsification is valid: although a theory or hypothesis can never be conclusively proved, it can be conclusively falsified. As Hume pointed out, the piling up of favourable instances in inductive reasoning can never lead to the confirmation of a universal statement. But only one negation of the consequent necessarily would lead to the rejection of a hypothesis or a theory. According to this view one example of a levitating heavy object (on the surface of the earth) then would topple Newton's gravitational theory!

What does Popper then recommend that scientists do in the face of the failure of induction? His radical proposal is that scientists should consider evidence only to the extent it tends to falsify general statements. He argues that systematic growth in science can only occur when science treats ideas as falsifiable.

This proposal is at the heart of his famous <u>Demarcation Principle</u> that allows us to decide whether a hypothesis or a theory is <u>scientific</u> or <u>non-scientific</u>. For example, theories like astrology and psychoanalysis, are <u>not</u> scientific theories because they are virtually irrefutable. Similarly, according to this view, creationist theory of the origin of the world must be considered as non-scientific because it , too, is virtually irrefutable. A theory as embracing as psychoanalysis is able to explain any outcome and is therefore virtually without predictive powers.

An extreme example may illustrate the point. To base human action on a theory of innate selfishness and from that explain human behaviour would obviously fail. It fails because the theory can be made to explain even the most generous acts. A theory (in this case really a hypothesis), can be so specific that a single crucial experiment will be sufficient to reject it. For example, if the cause of death in a suicide case is thought to be drowning in the ocean, an investigation failing to find salt in the lungs will falsify the theory.

On the other hand, Newton's theory of gravity must be considered a good theory because it is "wide open" open to refutation. The extreme example of a challenge to Newtonian physics is Priestly's attempt to protect his phlogiston theory (that phlogiston is given off during combustion) against the evidence that substances get heavier when they burn. Priestly claimed that phlogiston had negative mass!

The most disturbing feature of Popper's falsificationist theory of scientific inquiry is that the context of inquiry (see next section) can only be studied by psychology: there is no rational process involved in the discovery of hypotheses and theories. We may be persuaded to believe that since induction does not provide rational principles of scientific discovery that scientific discovery is indeed an irrational process. We will discuss the notion of rationality of science in the next section, in connection with Kuhn's ideas about science.

Popper claims that his method of falsification has solved the thorny problem of induction in science. We can argue, however, that first, in actual scientific practice we use rational procedures of decision making that have nothing to do with instantiation or refutation. Secondly, to say that we have more confidence in a theory that has stood the test of refutation, is to claim that we have had confidence in the theory before it was  tested. But this claim itself is surely based on inductive reasoning.

However, few failures in a well-established theory require the need for a reexamination of a theory. Even fewer actually do prompt major revision of a theory. When the eccentricity of the orbit of Uranus was not accounted for by Newtonian physics, instead of giving up Newtonian physics astronomers looked for and found another planet, namely Neptune. It seems that scientists are generally very reluctant in giving up a well-established theory, even in the face of strong counter-evidence.

**The problem of explanation in science**

The problem of <u>induction</u> deals with the question of how we can go from a limited set of data to generalizations that can go beyond those data. <u>Explanation</u> in science, on the other hand, is connected with the question of "why do phenomena take the form they do?". Explanation in science is connected with the construction of a theoretical framework that offers a good description of phenomena <u>and</u> allows us to draw deductive consequences. For example, Newton was able to construct a theoretical framework that contained law-statements to account for and describe the elliptical motion of planets. However, these laws not only enable astronomers to give an <u>accurate</u> account of events but also allow us to make astonishingly <u>precise</u> <u>predictions.</u> Therefore explanation and prediction seem to be intimately connected. Philosophers of science have developed various theories characterizing the nature of scientific explanation and how explanation is related to prediction. Let us briefly investigate this relationship.

It was Aristotle who first realized that one of the puzzles of scientific explanation is connected with our ability to infer biconditionally (X, <u>if and only if</u> Y) but explain only conditionally (X, <u>if Y</u> .) Aristotle's example goes like this:

Celestial bodies do not twinkle, <u>if and only if</u> they are near.

The planets are nearby celestial objects

Therefore, they do not twinkle.

It also follows that since planets do not twinkle they must be near.

<u>But explanation only moves one way:</u>

The planets do not twinkle because they are near. You cannot say that: they are near because they cannot twinkle.

A modern example may illustrate the point even better:

According to modern cosmology light received from a distant galaxy should be shifted toward the red end of the electromagnetic spectrum (spectroscopic observations) if and only if the galaxies are receding from us (Doppler shift). We can clearly infer one fact from the other. However, we cannot explain one fact from the other: the red shift occurs because the galaxies are receding; galaxies are not receding because of the occurrence of the red shift.

Explanation of an anomaly, like the retrograde motion of Mars, then, is accomplished by tracing it back by way of laws, to initial conditions established through observation. The astronomies of Copernicus and Tycho Brahe were indistinguishable as far as their predictive powers are concerned. However, the two theories, on which the predictions are based, are radically different. One of the questions philosophers of science still discuss is: "How then can we decide between two theories with equal predictive powers but different theoretical framework?"

It looks like scientific theories can evolve from "from mere predicting devices" to genuine explanatory theories. Babylonians were able to discover arithmetic algorithms to predict heavenly motions. However, they payed no attention to "explaining" celestial phenomena. You may recall that the Ptolemaic model of the solar system was a response to Plato's question: "By the assumption of what uniform and ordered motions can the apparent motions of the planets be accounted for?" The model was an excellent predictor even though it assumed that the planets as well as the sun revolved around the earth. The astronomy of the early Ionians, on the other hand, was based on speculation, models and theory, but was unable to make predictions. Harre argues that the ultimate objective of scientific inquiry ought to be theories that have reliable predictive value and are based on understanding the underlying mechanism (Harre, 1971).

It seems clear then that we simply do not have explanation/prediction symmetry in science, except in rare cases. Let us look at a number of cases that would be considered spanning the explanation/prediction spectrum.

1. It is possible to make very precise (reliable) predictions from the symptoms associated with diseases. However, it would be absurd to say that the symptoms explained the subsequent syndrome.

2. We can predict that a heavy object near the surface of the earth will take so many seconds to fall a given distance. However, we cannot explain why the acceleration is what it is, because we do not have an understanding of the nature of gravity. Our understanding, based on Newtonian physics, is really only a description, not an explanation.

3. When we heat a metal we predict that it will expand. However, to explain why this takes place would require a good understanding of atomic theory and thermodynamics.

4. In the theory of evolution no specific prediction has ever been made. However, the theory gives a good explanation of why, under certain conditions the species that are encountered were evolved.

The paradigmatic ( this word will be used often in connection with Kuhn's work in the next chapter) example of a good scientific theory is Newton's theory of gravity. It may come as a surprise that although this is an excellent predictive and descriptive theory, it is rather a poor explanatory theory. It is a poor explanatory theory in the sense that Darwinian theory of evolution or the kinetic-molecular theory of gases are excellent explanatory theories. We simply have a very poor understanding of the mechanism of gravitational attraction.

Rom Harre argues that the virus theory of poliomyelitis is a good explanatory theory, whereas the "beautifully systematizes laws of mechanics are not" (Harre, 1971). On Harre's account the kinetic-molecular theory of gases is an explanation, or *generative mechanism* of the behaviour of gases. However, it follows the <u>paradigm</u> (again refer to the next chapter) of the virus poliomyelitis, and not the paradigm of Newton's force formulation of mechanics (in spite of its mathematical nature). In this sense Newton's theory of gravitation is a poor explanatory theory. Science, it seems, consists of both kinds of theories.

Does this imply that Newton's theory of gravity is no more explanatory than the algorithms (rules) of the Babylonian astronomers were? In a sense that seems to be the case. However, Newton's theory is a complex network of interconnected laws and definitions, it has diverse connections to otherwise disparate sets of phenomena, and has great predictive and problem-solving powers. When scientists speak of "explaining" an event or a problem involving the motion of a planet, for example, they refer to the powers that reside in the Newtonian theoretical framework. They do not imply that Newton's theory of gravity "explains" events by way of underlying mechanism.

The attempt to deal with the problem of induction and explanation in gaining scientific understanding gave rise to the various philosophies of science since the time of Hume. It also generated the fundamental questions of epistemology (theory of knowledge) and ontology (the status of this knowledge) that philosophers of science still discuss today. Examples of such questions as: "What is the relationship between observations and theory?" and "Are scientific laws, models, theories real, or are they merely human inventions?" Moreover, the general activity of scientific inquiry, was seen in terms of two clearly separated sets of activities, named the context of discovery and the context of justification. These contexts are best understood through high-grade scientific thinking exemplified by Newton's gravitational theory (see fig. ). The first, the context of discovery, involves the origin and the evolution of ideas in science: how did Newton go about establishing his gravitational theory? The second, the context of justification, involves the use of logical and empirical criteria in scientific inquiry in evaluating evidence and in testing the claims of a theory: Are the laws of terrestrial motion, combined with the inverse square law, sufficient to account for orbital motion and the motion of a pendulum?

Richard Duschl (1990) in his book *Restructuring Science Education* calls the philosophers discovery/justification distinction "the two faces of the nature of science". He calls these: 1. Science as a process of discovering knowledge-what we know, and 2. Science as a process of discovering knowledge-how we know. He argues that the second characterization (context of justification) has dominated science education. Indeed, out of the discovery/justification dichotomy came the well-known product/process distinction.

We will now take a brief look at some of the key philosophies of science that attempted to deal with the questions that the fundamental problems of induction and explanation generated. We will then discuss to what extent science textbooks and science teachers consider the findings of the philosophy of science.

**Philosophies of science**

There were many philosophers in the 19th century that continued to try to come to terms with scientific activity, in spite of the fact that Hume showed (1750) that induction in science cannot be defended. August Comte (ci. 1820), argued that science was characterized by applying a specifiable method that guaranteed success, even in the face of the failure of induction. The method begins with specific data that produce ascertained facts by way of establishing experimentally verifiable laws. Comte was the founder of what we today call the positivists philosophy of science.

The work of the British philosopher and logician John Stuart Mill (ci. 1840) stands out when discussing the major attempt to reinstate induction. He tried to place the method of generalizing from observations on a logical footing, perhaps trying to do for inductive logic what Aristotle accomplished for deductive logic.

Mills philosophy of science is an outstanding example of the inductivist's point of view, epitomized by Karl Pearson in the "scientific method. His contemporary, William Whewell (ci. 1840 ), on the other hand, argued that observational data become *bona fide* data only if the data is seen through the eyes of theory. In other words, he argued that we see the world with our ideas. Whewell's account, on the other hand, exemplifies what is often called the hypothetico-deductive method of scientific inquiry, what we shall call the intuitive-imaginative philosophies of science

These two early philosophies of science can be seen as the progenitors of a host of philosophical schools in science. These can be roughly be placed into two major categories: The empirical-inductive and the intuitive-imaginative. Philosophers in the first group generally believe in the primacy of data and in a specifiable scientific method. The second group, on the other hand, insist that data are dependent on our theoretical background and argue that the passage from data to generalizations (theories) cannot be pinned down by method. This passage, it is thought, is utterly dependent on the human imagination and the prevalent world view of the times. We will look at these two groups in turn.

**The empirical-inductive philosophies of science**

Karl Pearson was a statistician who published an influential book about the nature of scientific inquiry in 1892. The book was entitled *The Grammar of Science* and can be seen as the original statement of what known as the "scientific method". He summarized the empiricist-inductive view of science very convincingly. It can be argued that the notion of scientific method as described in his work, has become taken for granted by many practical, every-day scientists and science educators well into the middle of this century (Stinner, 1989).

Pearson believed that science is essentially an empirical-inductive enterprise that had four characteristics:

1. Science has achieved a superior kind of truth.

2. Science was characterized by inexorable progress.

3. Science was in the possession of the only method of interrogating nature, namely the empirical-inductive method (the "scientific method").

4. This method could be simply described and easily taught.

You should readily recognize this picture of science: to a large extent it is still held by the general public, and is present in our science teaching.

Moreover, the claims for induction made by both Mill and Pearson were:

1. The Principle of Accumulation, or science grows by the accumulation of facts,

2. The principle of Induction, or the laws of nature can be inferred by applying inductive principles according to the "scientific method"

3. The Principle of Instance Confirmation, or the degree of plausibility of a law is proportional to the number of instances that have been observed of the phenomenon described by the law.

4. The Confirmation-Procedure ( context of justification) and the Discovery-procedure (context of discovery) are one and the same.

We will see later that these claims are still alive today in the public misunderstandings of science.

At the beginning of the 20th century a group of philosophers in Vienna took some of Comte's positivist ideas, Pearson's scientific method and Russell's and Whitehead's work in symbolic logic and founded the logical positivists school of the philosophy of science. They tried to "create a single set of rules to guide the practice of theory justification" (Duschl, 1990). A.J. Ayer was the foremost English exponent of the positivists of the Vienna Circle, or what became known as logical positivism. The name is to be traced to the central canon of this philosophical school: "What counts then as true statements are empirical statements and tautologies (self-evident truths, such as "all unmarried men are bachelors"). One consequence of this doctrine was that anything that could not be verified empirically or tested by the canons of formal logic was meaningless. The logical positivists wanted to divest themselves of all "metaphysical" reference in an effort to an ensure that all knowledge was verified, or at least verifiable.

We still find this doctrine enshrined in our science teaching, especially in textbooks. Textbooks "encourage students to observe or 'discover' natural phenomena and scientific concepts, without any understanding of the concepts or principles needed for seeing and discovering" (Duschl, 1990).

During the first half of the 20th century there have been influential scientists (Pearson, Mach, Bridgeman) who have further argued that scientific concepts do not refer to physical reality at all: they are thought to be merely heuristic devices to order experience. The philosophy that advocates this idea is called instrumentalism.

According to instrumentalism a theory has no more status than a rule that enables us to infer some observation statements from others. These rules establish correlations between actual and possible observations, they are not statements of fact in terms of which we can explain observations. Thus we can pass from $p_1v_1$ to $p_2v_2$ because the kinetic theory of gases. However, the theory itself is not supposed to have any *ontological* (see above). The question of the truth and falsity of the theory does not even arise, because the theory is regarded as asserting nothing in fact about the world. The value of theories is solely connected to their effectiveness as "instruments" for research. The best example of an instrumentalist approach is the Ptolemaic system of the solar system. In answering Plato's question (see above) astronomers devised a model that fitted the requirements of uniform circular motion, disregarding the ontological status of the model. The very successful Nuffield Physics in England (introduced about 1970) was implicitly and explicitly based on the instrumentalist view of scientific inquiry. (We will discuss the Nuffield project in the Questions and Assignment section.)

**The intuitive-imaginative philosophies of science**

William Whewell (cir. 1840) recognized that it was not possible to identify 'relevant facts' without assuming a background theory. A background theory, like Newton's gravitational theory, is not based on 'systematic analysis of data', as his famous British contemporary, J.S. Mill, claimed (and later enshrined in Karl Pearson's book The Grammar of Science). Such a theory should be seen more like the sum total of the answers we obtain to our ordered questioning in the context of a presuppositional structure (See fig. ) ultimately expressed in a compressed series of (mathematical) and definitional statements. A fully-developed theory, like Newton's theory of gravitation or the kinetic-molecular theory of gases, of course, does not come easily and immediately. The question-and-answer procedure involves experiments, often using data that are selected on the basis of an incomplete theoretical background. The struggle to achieve a conceptual basis for such a theory involves a continual ordering and re-ordering of questions in response to experimental results and corresponding changes in deciding what the corresponding changes in deciding what the appropriate physical quantities must be that will appear in the definitions and the laws. Moreover, the presuppositional structure of the theory itself may change in response to this approach. A specifiable scientific method of the kind Pearson described, it is argued, simply cannot accommodate this kind of scientific thinking.

Much like Whewell did, the "new" philosophers (Kuhn, Laudan, Hanson, Lakatos) have argued that scientific facts are meaningful only in the context of a theoretical background. Like Whewell, they advocate the study of the history of science in studying scientific activity, and reject formal logic as a primary means of analyzing science. Moreover, they emphasize continuing research programs together with on-going criticism as the core activity of science. They do not stress accepted results of scientific discovery. Like Whewell they advocate the investigation of the context of discovery, and de-emphasize the importance of the context of justification.

The philosopher of science who tried to explain why scientists in general are not Popperian, was the British -Hungarian Imre Lakatos. He said that scientists simply do not consciously attempt to invent theories of a high degree of falsifiability. Rather, he argued that such high-level theories as Newton's gravitational theory should be thought of as a *core theory*.  Core theories are "protected" by a layer of auxiliary theories. If an experimental result cannot be explained in the light of a theory scientists do not rush to reject the core theory. Rather, they tend to adjust the protective belt of auxiliary theories in order to fit the experimental result to the core theory. If scientists aimed at establishing theories with the purpose of falsifying them, theories would not survive very long. Theories must be given ample time to protect themselves. Lakatos recognized this and said: "We must treat budding theories leniently".

We have already mentioned that when it was discovered that the motion of Uranus could not be explained by Newtonian physics astronomers protected the core theory of gravitation by looking for a new planet. Moreover, when it was discovered that electric forces attract as well as repel, this was not thought of as an instance of falsification of Newton's gravitational theory. A number of theories dealing with electric and magnetic forces were devised, keeping gravitational theory intact.

However, it is not always possible to protect a core theory. Toward the end of the 19th century it became clear that Newtonian physics could not deal with certain experimental results (Michelson -Morley experiment showing the constancy of the speed of light and certain asymmetries inherent in electromagnetic theory). When it was clear that no auxiliary theory could patch up Newtonian physics to reconcile it with such findings Newtonian physics was replaced by Einsteinian physics. The historian of science who had a lot to say about this sort of radical change is Thomas Kuhn. We shall his widely influential ideas in the next chapter.

**Theories and physical reality**

How do philosophers view the ontological status (physical reality) of theories and the entities these theories contain?

Scientists like Karl Pearson, Ernst Mach, and P. Bridgeman have argued that scientific concepts like atom, electron and photon, do not refer to physical reality at all, but are merely heuristic devices to order experience. According to Bridgeman, if no operational definition (namely, empirically testable) can be given for a concept, then the concept is without empirical significance and must be excluded from science. Operational definitions are supposed to be the link between concepts and experimental data (pointer readings) by way of a deductive argument.

According to the inductivist-empiricist philosophies it follows, then, that given an operational; definition and the appropriate experimental data, it should be possible to deduce the concept best suited to explaining the phenomenon. On this account, to discover Galileo's laws of free fall we would simply tabulate distance and elapsed time and the concept of uniform acceleration would follow. According to the intuitive-imaginative philosophies, on the other hand, concepts, as well as theories are the creation of the human imagination (see above). The construction of scientific theory must be more than the tabulation of data according to operational definitions. If scientific thinking were only that then an on-going high-grade thinking activity before, during, and after the fact could never get off the ground. How can scientists formulate the concepts associate with, say, the Bohr atom without this kind of activity? It seems that on the inductivist-empirical view we could never rise above the notion of science as an activity that strives for constructing sophisticated predictive devices.

Thoebald argues that the issue of physical reality is a philosophical issue and should not be considered part of scientific thinking . However, he still maintains that theoretical entities have "the same right to be called real as have oranges", as long as they are features of well-confirmed theories. However, such entities as electrons, atoms, molecules, viruses, must have "existence" (ontological status) beyond the grip of a theory. As Ian Hacking puts it, referring to electrons: "If you can spray them they must exist." (Hacking, 1982). But the epistemological status and the ontological status of entities such as the electron are related in complex ways. The modern physicist "sees" a different electron from the one Millikan, the discover of the electron, saw.

Let us conclude with a note on some of the variations of the popular misunderstandings of the ontological status of theories in science. Robert Nideau and Jacques Desautels in a discussion paper written for the Science Council of Canada claim that there are four main categories of misunderstandings of science:

I. Naive Realism

II. Blissful Empiricism

III. Credulous Experimentalism

IV. Blind Idealism

V. Excessive Rationalism

We will discuss these categories of misunderstanding in the  Questions and Assignments section in more detail. But first here is a brief summary of what they say. We will argue that all of these views are connected to the inductivist-empiricist philosophies, and especially to a Pearsonian understanding of science.

The first is based on the belief that scientific knowledge is the reflection of things as they really are. This epistemological position is connected with the idea that scientific thinking is simply the reconstruction of things as they actually are. N and D argue that we see the world through language and symbols. Therefore, it is "just as false to think that the world is limited to the representation one has of it as to imagine that it is possible to know what the world is like outside of any representation" (Nadeau and Desautel). This view can be seen as an extreme version of the inductivist-empirical philosophy.

The second is based on the belief that all knowledge derives directly and exclusively from observation of phenomena. This view is clearly a direct outcome of Pearsonian science, namely believing that there is a specifiable scientific method. But we already argued that a "fact" in science is only that *in relation to a background theory*. Indeed, we argued that without a theoretical basis observation cannot even get off the ground. Moreover, this view assumes that the human mind is a *tabula rasa*, where knowledge based on *pristine* facts is recorded. However, we will see in chapter x that children have a conceptual basis from which they determine what are the "facts".

The third is based on the belief that experimentation makes possible a conclusive verification of a hypothesis. This view reminds us of Pearson's claim that the scientific method allows us do demarcate between science and non-science. According to our earlier discussion of inductive reasoning in science a hypothesis can be confirmed but never verified.

The fourth is based on the belief that the scientist is a completely disinterested and objective being. We will see in the next chapter that science is essentially a social activity. Scientific activity is a collective effort, with occasional high-grade insight by individuals. However, these insights must be discussed defended and generally be subject to peer-review. Again this view is connected to a Pearsonian understanding of science that assumes that the dispassionate objective scientist is able to look at facts and devise hypotheses and find laws.

The last is based on the belief that science brings us gradually nearer to the truth. As N and D put it:

> In these terms science appears historically as an accumulation of well-established facts, of which the most recent addition are the most reliable. Scientific knowledge is seen as the steadily increasing illumination of a given truth by a clearly visible process, marked at each stage by and advance from initial preconception to increasingly informed judgement. The quest of truth is viewed as a cumulative and consequently continuous process that has gone on, uninterrupted by precipitate change or sudden alteration since the days of Babylon (Nadeau and Desautels)

**Implications for the teaching of science**

Guidelines, textbooks and common practice stress, if not the Pearsonian "scientific method" explicitly, then the "processes" of science, understood essentially as inductive method. However, science teachers and textbooks seldom discuss the question of what scientific induction is, and what the problems of induction are. What these problems are, their fundamental nature and their complexity we have outlined in this chapter. We have argued that "scientific method" disguised as "inquiry" or "science processes" is necessarily an articulation of scientific induction. It is

puzzling, therefore, that textbooks simply do not discuss the problem of induction in any detail.

In a classroom science teachers could begin the discussion of scientific induction with examples such as the ones suggested above. The first example can be discussed in grade 8/9. The second one is ideal for discussing the mechanical procedures we use in elementary physics experiments in high school. These experiments involve the proportionality statements between dependent and independent variables. The third example deals with one of the great achievements  Science teachers and textbooks explicitly or implicitly tell students that there is/are scientific method(s) that involve mechanical-inductive procedures along the lines suggested by Pearson one hundred years ago. Rather we should show students that indeed many elementary investigations proceed along those lines. However, most high-grade scientific activities, such as Newton's mathematical description of the motion of the planets, Lavoisier's researches that led to the discovery of oxygen, and the work of Crick and Watson in producing the DNA model, cannot be pinned down by a specifiable method.

Moreover, experiments students perform in classrooms are of the type "To verify Newton's second law of motion". The format the students follow is arguably base on a modern version of Pearson's scientific method . Student implicitly assume that this is how laws in science are justified and discovered. In other words, students are told indirectly, that the context of discovery and the context of justification are one and the same.

It is recommended, then, that teachers teach toward clarifying the nature of induction, consciously incorporated in the curriculum. Our discussion of deduction in science suggests that it is equally important to incorporate into the curriculum how scientists frame explanatory theories and show what their strength and weaknesses are.

Generally science textbooks and science teachers implicitly stress the deductive nature of scientific theories. The student first becomes acquainted with the deductive formulation of theories when he reasons this way:

All metals are conductors of electricity

Copper is a metal

Therefore copper is a conductor of electricity

Later, in high school, the students learn Newton's laws of motion by way of the finished product of mathematical formulation. From these he reasons deductively while solving problems of motion.

The first example is typical of what is perceived as scientific explanation by the junior high school student. To the question "why are metals good conductors?" the teacher may offer a textbook answer based on the electron-model of conduction. The teacher might say: "You will learn this later in high school physics". In either case the student is likely to be baffled and looses interest.

Our second example is typical of what is perceived as scientific explanation by the senior high school student. He has at his disposal the laws of motion from which he/she is able, by simple mathematical deduction, to solve "type problems".

Neither student, however, is generally aware of: 1. the fact that he/she is engaged in deductive thinking, in some sense of "deductive"; 2. how such deductive systems are arrived at; 3. what would count as an explanatory theory that makes deductive reasoning possible in each case; and 4. what features the two theories have in common and what sets them apart. In our first example we should make the student aware that the statement: all metals are good conductors of electricity (and heat) does not rest on an inductive process of reasoning based on investigating as many metals as possible. Rather, it is based on a rich theoretical framework diversely connected with electric theory, thermodynamics and quantum theory. This then is a good explanatory theory. While we cannot give the student a detailed explanation we can still indicate this theoretical background on a lower level. In our second example, calculating the distance an object falls, using the equations of kinematics, could be arguably be called "deductive". In what sense, however, do we reason deductively when we find the expression for the period of the pendulum? Finally students should understand that Newton's theory of gravity is a poor explanatory theory despite its awesome powers of prediction.

# Chapter 11

## More about Kuhn’s Ideas

### Paradigms, Confrontations, and Revolutions in Science.

We have already briefly touched on the ideas of Thomas Kuhn . Since his work is very important for our discussion we will now elaborate on the history on the philosophy of science according to Kuhn

**Paradigms**

In his famous book, *The Structure of Scientific Revolutions*, Kuhn argues that it is not a recognizable method, or an identifiable set of rules, that describes a scientific research group's particular common and shared way of "seeing" the world of phenomena. Rather, it is the particular *paradigm* of the research tradition that guides their scientific thinking. He recognized the elusiveness of the notion of *paradigm* (it cannot be pinned down by definition, explicated in terms of *method* or an unambiguous *set of rules)*.

He thought a detailed investigation of the notion, however, will allow us to come to grips with the dynamics of scientific confrontations and the nature of science itself.

Kuhn generally seems to identify a paradigm with what it is that underlies and gives coherence to a research tradition. The priority of paradigm over method, rules and assumptions, however, immediately leads to **three** interrelated effects or consequences. These can be phrased this way:

1. What it is that holds the allegiance of a scientist to a particular research tradition in the absence of a well-articulated method and a body of rules.

2. A corollary of the first is the question of the nature of scientific education.

3. The observation that, historically, debates about rules, presuppositions, legitimate methods, problems, and standards of solutions take place only during the *pre-paradigm* period, and again when a paradigm becomes unstable and insecure.

Kuhn argues that the practising scientists in a given *paradigm* are active in what he calls *normal science*. The *normal scientist* learns to identify problems and techniques associated with a research tradition. Scientists recognize these because of a *resemblance* to already successful achievements within the *corpus* of science, and not because they are the product of a *method*, or a set of rules. Scientists in fact become members of a research tradition as well as "believers" in a paradigm. This is achieved by virtue of their training and their science education, the literature they read, and what they recognize as standard models and solutions of their craft.

Kuhn maintains that scientists learn their science through the study of the application of a theory to some concrete range of natural phenomena, and *never learn concepts, laws, and theories in the abstract and by themselves.* Students of physics, for example, learn their craft by studying specific applications concrete examples, what he calls exemplars, which involves working with instruments in the laboratory and practising problem solving. The well-known exemplars of elementary physics are connected with: The inclined plane, The pendulum, Atwood's machine, The ballistic pendulum, and more recently The electronic air table. We will say more about exemplars later.

Thus a physics student, Kuhn argues, becomes acquainted with and discovers the fundamental notions of Newtonian dynamics only through the application of these concepts to both problem solutions in the laboratory and **on** paper. Students do not learn physics by reading the definitions of *force, mass, instantaneous velocity,* etc.

The activity that Kuhn calls *normal science*, however, can go on only so long as the solutions to the problems posed by the paradigm are accepted by the research group. When the solutions to some important problems are challenged then debates begin to take place *over legitimate methods, problems, and standards of solution.*. Attempts to identify and then question the foundations and the *presuppositions* of a tradition usually signal the beginning of a crisis. Problems begin to pile up that stubbornly refuse solution by methods sanctioned within the paradigm.

Confrontations in science arise when two or more groups who *see* the world differently attempt to explain to each other the **how and why** of phenomena that are considered proper to their common domain of investigation. Confrontations in physics, for example, have occurred since about the time of Aristotle

(see A. Stinner, The Teaching of Physics and the Contexts of Inquiry: From Aristotle to Einstein, in *Science Education*, Sept. 1989.)

First, we have the problem of characterizing a group that is engaged in scientific thinking within the confines of a research tradition. We want to know what it is precisely that guarantees cohesion among its members. Then there is the question of what would prompt another group to seek actively a new way of seeing, in spite of a well-founded, often long allegiance to a tradition. Finally we have the question of the rationality of the conversion that induces a group to abandon a tradition for a new one.

**An Early Confrontation:**

In the science of electricity, for example, there were "almost as many views about the nature of electricity as there were important experimenters ....". According to Kuhn, however, their diversified views had one important thing in common : they were all guided by a version of a presupposition of Newtonian physics, the *mechanico-corpuscular* view of nature.

It is interesting that several "wrong" guiding principles lead the "electricians" of the eighteenth century onto the right path. They developed a consensus on an underlying mechanism for explaining their experimental findings that provided them with direction for new experiments as well. For example, the discovery of the Leyden jar, "a device which might never have been discovered by a man exploring nature casually or at random", was based on the fluid model of electric phenomena. But it was precisely the effort to explain the phenomenon of the Leyden jar that lead Franklin to the *electric charge* concept that we are familiar with today. Kuhn emphasizes this new way of "seeing":

... after the assimilation of Franklin's paradigm**,** the electrician looking at a Leyden jar "saw" something different from what he had seen before. The device had become a condenser, for which neither the jar shape nor the glass was required. Instead, the two conducting coatings-one of which had been no part of the original device-emerged to prominence.

This way of "seeing" the Leyden jar ultimately led to the concept of the condenser that became the prototype of all our electronic devices of today. The study of electrical action-at-a-distance could now be a legitimate study and the phenomenon we now call **charging by induction** could be explained as one of its effects. We can say that, like Galileo looking at a swinging body and seeing a pendulum rather than Aristotelian constrained motion lived in a different world from the Aristotelian, so the new "electrician" of the late eighteenth century, after accepting the condenser model, worked in a different world from the *fluid theorists*.

The effect of hitting upon a simple plausible mechanism underlying all diverse electrical phenomena had revolutionary consequences. First it gave direction to research: the discovery of Coulomb's law, for example, is inconceivable without the guiding notion of point charges affecting each other at a distance. Secondly, it transformed the group "previously interested merely in the study of nature into a profession or, at least, a discipline.

The members of the group of a newly-formed science, like the members of the new science of electricity around 1800, stop arguing endlessly over presuppositions, discontinue working on "puzzles" unconnected with the domain defined by the group's new way of "seeing", stop dealing with mavericks and cranks, and begin to communicate by way of their own journals.

Once the warring groups (in our example the "electricians" with their various modes of explaining electrical phenomena) agree on presuppositions and a set of theories to guide their research, they are on the road that leads to the assimilation of a time-tested and group-licensed way of seeing. The members of the newly-formed scientific discipline now spend most of their efforts in deciding what the genuine problems of their discipline are and become oriented to what Kuhn calls "puzzle- solving". This state of affairs requires for the members *to take the foundations of their field for granted.*

The new state of consensus is characterized by a *constellation of group commitments* Kuhn now calls a *disciplinary matrix*. The word *disciplinary* here refers to *the common possession of the practitioners of a particular discipline*; *matrix because it is composed of ordered elements of various sorts, each requiring further specification.*

Finally, it is desirable that the new scientific specialty become reconcilable with the dominant scientific view of the age. In the case of the new science of electricity, roughly around 1800, Coulomb's law, for example, had to be successfully incorporated into Newtonian physics. Initially this presented difficulties because of the presence of repulsive forces, not accounted for in Newton's *Principia*. Only after the recognition of a new kind of force in nature, that acted on charged particles according to Coulomb's law (like Newton's law of gravity this turned out to be an inverse square force) could the new science of electricity be incorporated in the larger disciplinary matrix of Newtonian physics.

Let us now briefly mention a few outstanding examples of confrontations in science.

**Examples of Contemporary Confrontations**.

Sometimes there are many competing theories seeking to lay the foundations of a new discipline, as in the case of the eighteenth-century science of electricity, but mostly scientific confrontation is the squaring off between two rival theories:

Newton's physics, based on the presupposition of mass points interacting via central forces of attraction and repulsion and Descartes's physics, based on the presupposition that the universe is composed of infinitely hard corpuscles interacting by contact;

Newton's particle theory of light and Huygen's wave theory; Dalton's atomic theory and Priestley's affinity theory in chemistry; The continental action-at-distance interpretation of electromagnetic theory based on Coulomb's and Ampere's work and the British field tradition based on Faraday's work, Planck's quantum theory and classical electrodynamic theory;

Einstein's special theory of relativity and Newtonian physics; Schroedinger's wave and Heisenberg's matrix interpretation of quantum mechanics; Gamow's big bang theory and Hoyle's steady-state-theory in cosmology; cold Fusion in physics and chemistry; continental drift in geology; punctuated evolution in biology; action-at-a-distance versus instantaneous action in quantum mechanics.

More recently, we have the rivalry between the S-matrix and the quantum field theories in particle physics. All of these controversies, except the last, are thought to have been successfully resolved. We should mention that the confrontation between creationists and evolution would clearly be considered a pseudo-confrontation in the context of Kuhnian science.

The resolution of controversies like the ones we have just mentioned implies the adoption of a new way of "seeing" by the members of the group that were finally converted to the rival theory. The process by which members of one group come to "accept" the views of the rival group seems to be a *dialectic* process and to some extent a logical process. It is a dialectic process because the criteria of choice depend on the complex influences of the presuppositions of a particular historical period. It is also a logical process because, as we shall argue against Kuhn, there are rational criteria involved in choosing one way of "seeing" over another.

**Kuhn's Disciplinary Matrix**

Kuhn describes the disciplinary matrix in terms of four main components:

metaphysical assumptions,

symbolic generalizations,

values,

concrete problem solutions (exemplars)

In other words, a research tradition can be characterized by its:

1. presuppositions

2. research methods that depend on particular formalization and language

3. values in articulating its findings and

4. worked-out typical problems that both illustrate and characterize certain areas of interest.

The first component can be seen as notion of the absolute presuppositions of a science as mentioned earlier. For example, for a Newtonian physicist (by the end of the eighteenth century) it was an absolute presupposition that all motion is regular, in the sense that all motion is law-like; that space is Euclidian and that time is absolute; that the universe is composed of mass points (atomic masses) that interact *via* central forces of attraction and repulsion, varying with distance.

The second component comprises the formal aspects of a discipline: laws, sometimes symbolically and sometimes verbally expressed, such as F = ma, and "for every action there is an equal and opposite reaction"; and definitions, such as the definition of current and resistance in Ohm's law, I = V/R. Laws like F = ma, however, must be understood as a law-sketch, or law-schema, rather than a specific law.

For example, the law F= ma can be used to describe a simple case of free fall, the more complex case of the motion of a pendulum, and the very complex case of the projectile motion through a resisting medium. The mathematical representation of this law in the description of the latter, for example, would be unrecognizable to the student of elementary physics. The confidence with which we have our students carry out these progressively more difficult applications of an apparently simple law attests to both the belief we have in the law-like behaviour of matter in motion (at least on a large scale) and to our pedagogical success in transmitting this knowledge efficiently to successive generations.

The third component, namely values, are the qualities probably most prized in a discipline: they provide a *sense of community* to the practising scientists. One values a theory for its predictive power, internal consistency, and fertility in suggesting problems.

The main function of values, however, is to provide guidance during a period of intense confrontation, for example, when the members of a group have to choose between incompatible ways of practising their discipline. Values also concern aesthetic judgements, and these judgements depend on the individual scientist. It may in fact be (as was certainly the case in quantum mechanics and relativity theory) that each time a new way of looking at the world is discovered, the nature of the new symbolic formulation is decided by criteria which are ultimately aesthetic in origin.

The fourth component of the disciplinary matrix is perhaps the most important for us, because of its relevance for science education. Kuhn calls this aspect of the disciplinary matrix "exemplars", and thinks of it in terms "of a group's shared commitments". The notion includes both "...the concrete problem-solutions that students encounter from the start of their scientific education, whether in laboratories, on examinations, or at the end of chapters in science texts", and "...the technical problem-solutions found in the periodic literature that scientists encounter...."

For example, exemplars which all students of elementary physics instantly recognize are the paradigmatic, or what we can label as "type problems" or *algorithm* teaching. As we have already indicated these "type problems" cluster around such prototype problems and prototype instruments in physics as the inclined plane, the simple pendulum, the conical pendulum, the oscillating spring, and Keplerian orbits, instruments such as the vernier calliper, the calorimeter, the Wheatstone bridge, and the spectrometer. More recent examples of instruments are the linear air track apparatus, the electronic air table and the electric deflection tube.

In what sense, then, can we talk about progress given Kuhn's picture of normal and revolutionary science?

**Progress in Science**

According to Kuhn science can progress on two levels: during the long period of *normal science*, and also during the shorter period of a successful *revolutionary science* that ushers in a new research tradition. On the first level scientists who are trained in a common intellectual tradition attempt to solve the problems that the tradition generates, which then are expected to be soluble in its terms. On the second level a mature science, like physics, progresses with the succession of traditions, (Aristotelian, Galilean, Newtonian, Einsteinian), each with its own methods of research (disciplinary matrix). Each of these traditions guides a community of scientists for a period of time, and each in the end is abandoned.

The need to abandon a tradition in favour of a new one is signalled by the accumulation of long-standing problems. These are problems that prove unyielding to the research methods of the old tradition, however cleverly applied by the most skilful "puzzle solvers". With the piling up of such problems a crisis period is reached when scientists actively look for alternative ways of solving them. Eventually one of these, based on a new set of metaphysical assumptions and new methods of solutions, wins the allegiance of most scientists. A new disciplinary matrix develops that is able to solve these problems. What counted as scientific knowledge in the old tradition is reconceived, re-evaluated, and sometimes discarded. Textbooks are rewritten, science education is changed, and the scientist sees the world differently.

**Problems with Kuhn's Picture of Science**

There are problems, however, with Kuhn's picture of how science progresses. Kuhn argues that normal science, alternating with periodical revolutions is the only way a mature science like physics grows. Yet science must grow in different ways. For example, one can understand Einstein's special theory of relativity as an attempt to reconcile Newtonian mechanics with Maxwell's electromagnetic theory, and his general relativity theory as an attempt unify his special theory and Newton's theory of gravity. Einstein did not develop these theories in response to an accumulation of commonly perceived problems or anomalies. Moreover, a research tradition may find itself in a state of near crisis, not because of the piling up of difficult problems, but because of problems at the foundation of the science. At the moment both general relativity and quantum mechanics are under attack because of theoretical difficulties (Dicke, Bohm).

Finally, Kuhn does not explain why sometimes anomalies precipitate a revolution in science and other times they do not. For example, the precession of the perihelion of Mercury was an anomaly known in the middle of the last century, but the discovery merely prompted astronomers to seek solutions within Newtonian physics.

**Rationality in Science**

We saw early in chapter III that the fundamental problem in science is connected with our claim that science is a rational enterprise, even in the face of the failure of scientific induction. Pearson's program was to discover more and more about the world by using the scientific method, in effect ignoring the problem of induction. He believed that we cannot make metaphysical assumptions about the world since these cannot be tested empirically. We argued, for example, that unless we in fact make such assumptions as the uniformity of nature, inductive reasoning in science cannot be cast in deductive form, and the problem of induction in science remains unresolvable.

In what sense then is Kuhn's picture of scientific progress rational? Kuhn seems to defend the rationality of *normal science* on two grounds. First, the scientist who works within a disciplinary matrix can do so very efficiently, in the sense that the class of problems and the techniques for their solutions are already available. Secondly, every research tradition, or disciplinary matrix is expected to be eventually superseded by one that can explain all the standard problems of the present tradition and solve the outstanding anomalies of the old tradition. Moreover, a necessary (but not sufficient) condition of rationality in science must be collective agreement, and that is achieved if Kuhn's picture of normal science is correct.

Kuhn admits that the rationality of revolutionary science, however, cannot be so easily defended. According to Kuhn, when a theory like Einstein's general relativity theory replaces Newtonian gravitational theory, the two theories become *incommensurable.* This is so because, as we have already noted, such fundamental notions (or terms) as "mass" and "energy" take on completely new meanings in the new tradition. Moreover, since scientists are looking at the world through different exemplars, they 'see' different scientific facts.

It is clear that according to Kuhn's picture of science there is no logical way one can discover a new theory, nor show that one theory is superior to another. Members of the "old tradition" are therefore either *persuaded* or *converted* to accept a new way of seeing. Persuasion, however, may or may not be followed by conversion. Persuasion, according to Kuhn, is connected with one's resignation to the obvious superiority of one theory in solving outstanding problems over the other's. For example, Einstein's relativity theories can solve all the problems Newton's can and is able to "explain" such anomalous behaviour as the precession of the perihelion of Mercury.

Conversion, on the other hand, is connected with whether or not one can make a *gestalt switch* when embracing the new theory. Scientists in their middle years, for example, who had received their scientific education based on Newtonian physics only, were able to intellectually accept quantum mechanics and relativity, but were never "converted" to it. Kuhn likens such a person to the translator who translating a theory or worldview into his own language is unable to make it his own. We must remember, however, that Kuhn does not say that absence of logic can be equated with absence of reason.

Both normal science and revolutionary science then must be seen as irrational for the following reasons. There is no need for the working scientist to examine the foundations of his craft critically, for he must take them for granted. This constraint limits his range of inquiry and the rate of growth of his tradition. Kuhn claims, however, that without the concentration that only the security of the context of normal science can give, progress would be slow, if not impossible. Moreover, the search for a new theory is supposed to take place only when the security of normal science is disturbed by the piling up of unsolved problems. We have already mentioned Einstein's theories of relativity as a counterclaim to that. Einstein's case then can be seen as an example of revolutionary science that makes "Kuhnian theory-choice" much more dependent on the personal insights and aesthetic orientation of genius than on a concerted effort of a scientific community to find a new theory to explain certain anomalies.

Criteria for theory choice should also go beyond those that promote the solution of outstanding problems. Such criteria as problem-solving ability in general, simplicity, and aesthetic components, we have previously argued, must be considered in theory choice. We have also argued that such criteria must be imbedded in a presuppositional structure of a science. If this picture of science is correct, then it is rational to accept metaphysical presuppositions, such as *the world is intelligible* , precisely because these are empirically not testable. Nicholas Maxwell, for example, argues that unless we accept as a metaphysical presupposition that the world is rational, *science cannot get off the ground,* and is doomed to remain an irrational enterprise.

*...the aim of seeking intelligibility in the universe is rational, not because we have good reasons for supposing that this aim can be realized (in that intelligibility really does exist") but rather because, as far as science is concerned, we place such supreme value on intelligibility that we are willing to, quite rationally, to hunt for it even though we cannot know what we seek "really exists".*

**QUESTIONS AND ASSIGNMENTS**

1. Referring to WTS ("What is scientific thinking?", A discussion paper published by Canada Council, and written by Hugh Munby): The writer's approach to discuss what scientific thinking and its consequences are is a little different from what we understand by *scientific thinking* from our class discussion so far. The main points he makes, however, are similar to the ones we made in class. Discuss briefly.

2. Compare the characteristics of *scientism* , as portrayed in this discussion paper, with those of the *scientific method*, as expounded by Karl Pearson

3. On page 15 (WTS) we are told that as science teachers we must *ensure that science teaching at the high school level is based on the objective of instilling in the students a critical approach to scientific activity as opposed to scientific mythology*.The authors suggest that, in order to accomplish that, *epistemology point the way to a revolution in the teaching of science.* Based on what the authors offer in this discussion paper, do you agree? How would you change (make specific recommendations) the current way we teach science?

4. According to Kuhn, what is the role of the textbook in the training of "scientific minds"?

5. According to Kuhn, what is the role of the *science educator* in preparing the *normal scientist?*

6. According to Kuhn, how do textbooks treat the history of science?

7. Give an example of a well-established disciplinary matrix (DM) or paradigm in one of the sciences. Analyze this DM in terms of the four aspects discussed above.

8. What are the exemplars of elementary physics, chemistry, biology? Name them and discuss briefly their use in science teaching.

9. Chose one of the controversies we cited (or find one not mentioned above), and

i. Discuss how you would use it to discuss Kuhn' ideas of how science progresses.

ii. Show how you would introduce the controversy and to what extent (if at all) it would change your science teaching.

iii. Speculate on how the introduction of Kuhn's ideas (**normal and revolutionary science,** paradigm, disciplinary matrix, exemplars, etc) into the curriculum would affect science teaching.

# Chapter 12

## Notes on Constructivism, Postmodernism and Multicultural Science

Since the ideas and arguments connected with the above are very important for science education, we will look at these and make connection with what we have said so far.

### Constructivism

Constructivism is a cognitive theory (not a learning theory) that informs and inspires certain approaches to teaching. It emphasizes that science is a creative human endeavour that is historically and culturally conditioned, and that its knowledge claims are not absolute. Constructivism attempts to steer a path between teacher-dominated (transmission) instruction (the traditional didactic model of education) and student-led discovery learning (the progressive model of education).

Constructivism rests on two assumptions, one philosophical and the other psychological:

1. Knowledge is actively constructed, not passively received from the environment.
2. Coming to know is an adaptive process that organizes one's experiential world; it does not discover an independent, pre-existing world outside the mind of the knower.

These assumptions are connected and cannot be clearly separated.

The following short statements are summaries of findings in constructivist psychology:

3 Learning is experience-based, context-bound and domain specific.

4 Learning is an adaptive process in which the learner's conceptual schemes are progressively reconstructed in keeping with a wider range of experience.

For science educators the task of constructivist psychology is to inform teachers how they could best provide a clear passage from the intuitive, common sense world of the child to the highly abstract world of scientific ideas. Clearly, science teachers must first respect the preconceptions students have, then identify them and, finally, built on them. A great deal of research has been accumulated to help teachers identify preconceptions, and models of teaching constructed to guide them in their effort to built on these early conceptions. Constructivist psychology and research is able to assist teachers in achieving a smooth passage from intuitive, common sense understanding to scientific understanding, provided teachers are informed and apply the assumptions of constructivism and the research findings critically and undogmatically.

**Postmodernism**

As in constructivism, we see a bewildering array of agendas clustered around "postmodernism". A recent publication defines postmodernism "as a many faceted movement of people who share, for various reasons, a dissatisfaction with knowledge claims that embrace universalism" (Pinar). Specifically, Pinar argues that the movement is characterized best by "the end of: the subject, models of reality, history, the transparency of language, final meaning, reason to understand the world, belief in understanding the world".

Scientists and philosophers of science generally agree that, while science is not dependent on a specifiable method or a set of rules, the concepts and theories in science must be *consistent*, have a *unifying power*, and be *predictive*. This image of science - as a consistent, unifying and predictive approach to knowing is under attack by postmodernists, and with it the very idea of science itself.

Scientists generally believe in "the ideal of science as the only truly objective and lasting product of our culture - or of any culture" (Michael Ruse). Scientists claim to have genuine knowledge about the world and about human behaviour. They also believe that science and its products have the only hope for the betterment of the human condition. The counterclaim of the academic left (the postmodernists) is that science's objectification of life, exacerbated by the emergence of modern technology, has dehumanized Western society. T.S. Eliot argued some 50 years ago that this dehumanization has robbed us of the "sensibilities that make contact with what Matthew Arnold (over 100 years ago) called "the best which has been thought and said in the world".

Since the late middle ages there have been a number of confrontations between the sciences and the humanities that foreshadow the confrontation between science and the postmodern movement. The following is a brief summary of these confrontations:

1. The separation of knowledge by the end of the fifteenth century into the *trivium* (grammar, rhetoric and logic), relying on verbal methods of argument and syllogistic logic, and the *quadrivium* (arithmetic, geometry astronomy and mucic, conceived as a study of acoustical proportions), relying on calculation and measurement in presenting arguments. The *trivium* approximates today what we call the humanities and the *quadrivium* the sciences. In the fourteenth century, however, all scholars were (natural

philosophers and theologians) were thoroughly grounded in the full range of the liberal arts (the *trivium* and the *quadrivium*) and shared the same realm of discourse.

2. The confrontation between the sciences and the humanities surfaced again, much later, in the Shelley-Peacock Exchange of 1820. Peacock argued (mostly tongue-in-cheek) in his *The Four Ages of Poetry* that poetry had outlived its usefulness in the modern age of science. Shelley took the challenge seriously and responded with his much discussed essay *In Defence of Poetry*. Although he recognized the place of science he argued that "not through reason (analysis), but through the imagination (synthesis) do we perceive the 'indestructible order' and harmony of the universe". It should be noted that those who investigated the natural world were called *natural philosophers,* who still had a holistic view of nature and were well versed in the humanities.

3. The Huxley-Arnold controversy of 1882 is based on an exchange of views contained in Huxley's lecture *Science and Culture* and Arnold's response in his *Literature and Science*. Huxley argued that science had completely reshaped our understanding of the universe and man. According to Huxley, therefore, Arnold's meaning of culture, "to know the best that has been thought and said in the world" must include science. It seems that Huxley's understanding of science, was based on the belief that there is a specifiable scientific method that guarantees progress in all investigations where the scientific method is used. Arnold, on the other hand, believed that "...all learning is scientific which is systematically laid out ..., and that a genuine humanism is scientific" (Arnold, 1970). It is interesting to note that around 1880 the natural philosopher became a scientist and specialist in physics, chemistry or biology.

4. C.P Snow's *Two Cultures* debate is the basis of the most recent public confrontation between the sciences and the humanities. The *Two Culture* theory (1957) is based on the assumption that the intellectual life in Western society is increasingly being split into two polar groups, namely the scientists and the humanists. Snow argued that between these groups a gulf of mutual incomprehension exists. One culture, the scientific, should be thought of as continually in flux, incorporating new discoveries on the basis of general agreement and “verifiability”. The other culture, the humanistic, changes but does not depend on collective agreement since its emphasis is on content not process. Specifically, Snow claimed that the humanist is more often illiterate in the sciences than the scientist is in the humanities. In order to remedy this situation he advocated the acquisition of cores of knowledge as the basis for both scientific

and humanistic literacy. For example, it was axiomatic for Snow that there are scientific equivalents to the questions, "Can you read?", "Do you understand Shakespeare?" The scientific equivalent to these are "Do you know Newton's laws of motion?", and "Do you understand the second law of thermodynamics?". Later in his argument Snow concluded that the teaching of the humanities must ultimately be subsumed by the demands of the scientific revolution.

Snow's notion of a "two culture" split in our knowledge seems to have been enshrined in our thinking as well as in our science textbooks. In a recent much discussed book by two scientists (Gross and Levitt) who attempt to respond to the academic left (postmodernism) by making the unreasonable, if not paranoid suggestion that all hiring in the humanities be left to scientists:

> *On the whole, scientists are deeply cultured people, in the best and most honourable sense ...The range of knowledge of music, art, history, philosophy, and literature to be found in a random sample of scientists is, we know from long experience, extensive, and in some fortunate venues, enormous* (Gross & Levitt).

How then should scientists and science educators respond to the attacks from the so-called academic left? The responses by scientists seem to have been one of two extremes: A cavalier (and arrogant) indifference or a simplistic (and equally arrogant) solution of the kind offered by Gross and Levitt. First, a middle of the road defence against the threats made by the postmodernists should be adopted. Second, a multifaceted attack should be mounted by scientists and science educators alike. Evangelical feminists, extreme constructivists and multicultural science advocates should be challenged on their own grounds. It is interesting to note that the witnesses against creationism in the recent US debates were theologians and philosophers and those defending creationism were holders of Ph.D.'s in the sciences.

Of course, there is a lot of truth in the critiques mounted by the academic left. The world is a complicated place and Western science has only managed is to map a small part of it. There are many ways of knowing and understanding the world and the scientific mode of understanding is not the only one, however successful. Science is a human creative activity, validated by consensus and often deeply connected to the unarticulated assumptions of a given culture. That does not mean that we have to accept relativism and agree with the charge that Western science is intrinsically connected with materialism and reductionism. It simply means that we scientists have to reassess the philosophical assumptions of their craft and science teachers must teach science responds explicitly to the main charges made by the postmodernists.

In science education we could have three approaches that would rely equally on the sciences and the humanities that would give a student richer and more tolerant picture of the place of science in our understanding of the world. These are contextual teaching, thematical teaching, and popular science literature teaching. The first is concerned with creating contexts that have a central unifying idea that attracts the student. These contexts then generate questions naturally that involve science as well as humanistic disciplines. The science story, as outlined here, is a good example of this approach and works well with younger students. The second is a historical approach, aimed at older students, that discusses science *thematically*, identifying general themes which transcend the boundaries of individual scientific disciplines, such as the corpuscular nature of matter and the conservation of energy principle. The third approach is attempting to use a wholly new kind of science writing, with senior high school and university undergraduates, that we can identify as *the third genre* of science writing (Eger, 1989). Well-known examples are: Stephen Hawking's A Brief History of Time, Steven Weinberg's The First Three Minutes, and E.O. Wilson's On Human Nature. Since about 1970 there have been more than two hundred science publications written for the lay public by top scientists in the world.

Premature specialization in science occurs as early as in junior high school. It is a sad commentary on our compartmentalized teaching that already in junior high school students believe that science is neatly divided into *physics*, *chemistry and biology*. They also believe that intellectual and creative activity in the sciences and humanities is intrinsically different. What we must strive for is an education that uses all of the above approaches, with science textbooks assuming a secondary role, as reference books only. Perhaps this kind of multi-faceted approach would be a start toward an education that will embrace both the sciences and the humanities, without the contrived problem of having to bridge the gap between them.

Ultimately, however, I see the science story approach in its final form subsuming the other two approaches, the thematic and the popular science literature teaching. The fully developed "science story" could well be the link between scientific and humanistic modes of thought that we as teachers of science, mathematics, the humanities and art should exploit. This approach to the teaching of science would present a positive response to some of the deeper questions raised by the academic left.

**Multicultural Science**

> (A large part of this brief presentation is based on a recent book by the Australian science educator Michael Matthews).

The debate about multicultural science education is one part of a larger argument about schooling and culture in the West. Michael Matthews, in a recent book, says:

> Criticism of schooling in the 1960s centered on issues of inequality, access, and the ideological and political function of schools. More recently, critiques have focused on curriculum matter, and the school's role in the creation of public knowledge. Some maintain that the supposedly public knowledge transmitted in the curriculum is really partisan knowledge; it is knowledge created by, and furthering the interests of, particular groups. This can be seen in the arguments about "political correctness" that have engulfed many universities.

Many writers feel that the school science contributes to the pattern of domination and subjection. Some point to the deskilling and alienating effects of theoretical and impractical science curricula. Michael Young wrote on the culture of positivism in school science and its contribution to the functioning of science as a gatekeeper, restricting access to scientific knowledge and leaving the majority of the population scientifically ignorant and dependent upon a usually middle class, white, male, professional elite.

The following quote by the Canadian science educator Jacques Desautels sums up well science education in the 60s and 70s:

> By perpetuating overloaded curricula for years, often poorly suited for the intellectual development of the majority of students, the system has guaranteed that only a minority will eventually have access to scientific careers. By arranging curriculum content strictly
>
> according to logic and discipline, with no reference whatever to the history of science, apart from parenthetical anecdotes, it ensured that students do not absorb a critical view of knowledge . By divorcing curriculum content from everyday or cultural reality, the knowledge acquired is useless for the individual in his or her daily actions. (19840.

However, as Michael Matthews points out, these criticisms of science education were written on the assumption that science itself is epistemologically unproblematic: the problems were pragmatic ones of how best to teach science, and how to create pedagogies and structures that did not exclude, or discourage women, minorities, or the poor. The contemporary debate about multicultural science education is occurring in a different, postmodernist, intellectual environment, where the truth status of Western science is challenged, and its monopoly on scientific understanding is questioned. Bauman says:

> The postmodern perspective reveals the world as composed of an indefinite number of meaning-generating agencies, all reltively self-sustained and autonomous, all subject to their own respective logic and its own methods of truth validation (1988).

The issue facing science educators is to ascertain whether, and if so to what extent, the cultural and postmodern critiques that are applied to literature and the social sciences also apply to Western natural science. Is Western science just one among a number of equally valid and truthful sciences, each of which has its own logic and its own methods of truth validation?

Universalism is the epistemological position associated with Western, mainstream science. This view was well expresses about 70 years ago by the American philosopher of science Norman Campbell: "Science is the study of those judgements concerning which universal agreement can be obtained". George Sarton, a noted historian of science said, at about the same time:

> The developments of knowledge knows no political or rational boundaries. It is the only developments which is truly international. If we wish to bring the peoples of the earth together should we not draw their attention which are their common heirlooms, to the things which unite them? The history for the quest for the truth is the history of no single nation; it is the history of mankind.

This universalist view recognizes that while aspects of culture do influence science, but cultural considerations do not determine the truth claims of science. According to this view Newton's laws of motion are the same in Canada as they are in China. Michael Matthews puts it this way:

> The core universalist idea is that the material world ultimately judges the adequacy of our accounts of it. Scientists propose, but ultimately, after debate, negotiation and all the rest, it is the world that disposes.

Matthews suggests that is a spectrum of alternatives that have been adopted by science teachers when teaching science in multicultural situations:

Imperialist, where traditional understanding of natural phenomena are ignored and Western science is taught as it is in the metropolitan centers: PSSC physics in Polynesia,

Nuffield physics in Newfoundland, CBA chemistry in Colombia, and so on. Traditional beliefs are only attended to in order to prepare the ground for new knowledge which will supplant the old.

**Integrationist**, where alternative understanding and ways of thinking about nature are recognized, respected abd made use of, but in the last resort only as more effective means of having students learn about Western science. Ethno-science is dealt with in an anthropological way: what other cultures believe and reasons for their beliefs are pointed out. Efforts are made to interpret traditional beliefs and practices in terms of Western scientific understanding, in order to facilitate the understanding of Western science.

Robust or noninterventionalist, where ethnic and traditional science is recognized as an intellectually legitimate alternative to Western science and cultivated in its own terms along with varying degrees of Western science and technique. In some places both traditions are fully taught and a "best of both worlds" approach is taken; in other places

traditional sciences are taought.

Can Western science and multicultural science coexist?

Matthews answers partly this way:

> There is no doubt that subjectively, within an individual, all sorts of mutually inconsistent worldviews can coexist. Individuals are frequently unaware of the contradictions. Even when contradictions between intellectual commitments are apparent, individuals can live with enormous amounts of cognitive dissonance. ....For example, astronomy and astrology happily coexist for

numerous US science graduates. Fundamental Christianity thrives in centres of high-technology and space research (the witnesses for creationism at the Arkansas trial were all scientists, whilst the witnesses against creationism were mostly theologens and philosophers!)

The following are the basic ontological and epistemological questions which must be answered when comparison is made between multicultural science and Western science:

**Ontological questions:**

1. Is the world constituted in such a way as to serve human interest?

2. Are processes in the world teleological? That is, do events and behaviours occur in order to bring about some fitting end state?

3. Are animate and nonhuman animate processes activated and controlled by spiritual influences?

**Epistemological questions:**

1. Does knowledge come from the observation of things as they are in their natural state?

2. Are knowledge claim validated by successful predictions?

3. Do particular or authority figures define knowledge or become the custodian of knowledge?

4. Is knowledge a fixed and unchanging system?

The answers to these questions are left to you (with discussion).

In conclusion, here is a quote by Robin Horton, discussing the differences between African and Western science:

> The key difference is a very simple one. It is that in traditional cultures there is no developed awareness of alternatives to the established body of theoretical tenets: whereas
>
> in scientific cultures, such an awareness is highly developed. It is this difference we refer to when we say that traditional cultures are “closed” and scientifically oriented cultures are “open”.

(1971).

**Questions for *Postmodernism*:**

1. Do you agree that the term "postmodernism" is an "oxymoron"?

2. How would you defend the following claims made by science:

    a. Science has genuine knowledge about the world as well as about human behaviour.

    b. If an idea or claim cannot be investigated scientifically it is not an example of worthwhile knowledge.

    c. Scientific and non-scientific knowledge can be clearly demarcated.

3. How would you argue with a postmodernist in the following:

    a. Science objectifies life and technology dehumanizes us.

    b. African (Mayan, Chinese etc) science is just as "scientific as Western science and should be taught alongside conventional science in the schools.

4. Scientists believe that science to be called "science" must be consistent, unifying, and predictive. According this picture of science is traditional Chinese medicine (acupuncture) or non-traditional Western medical orientations "scientific"?

5. The poet and writer Mathew Arnold (see page 6) argued that "all learning is scientific which is systematically laid out...". Comment.

6. C. P. Snow argued the humanities must ultimately be subsumed by the sciences. Do you agree? Discuss.

7. Look at the scientific equivalents of "Can you read?" and "Do you understand Shakespeare?" Is this way of comparing knowledge in the sciences and the humanities illuminating? Comment.

8. Do you believe that scientists are generally more literate in the humanities than humanists are in the sciences? (See quote on bottom of page 6). Discuss.

9. What are your ideas about how to go about "defending" science when students ask "postmodernist" questions?

# Chapter 13

## Surprises in the History of Science

**TITLE:** ***"How can we incorporate famous surprises in the history of science into the science curriculum?***

**Arthur Sinner, Juergen Teichmann, Barbara McMillan, Ian Winchester**

Given as a presentation in the 12th IHPS conference in Thessaloniki, Greece, July, 2011. Published in the Proceedings.

There is still a wide-spread and pervasive belief that scientists use a specifiable and teachable method in going from observation to establishing laws and theories, namely the *scientific method*.

This picture of science found its way into science textbooks and versions of it were perpetuated by generations of textbook authors and most science teachers. This method is supposedly known, can be fully described and guarantees success in discovering scientific laws. Most textbooks generally present science, implicitly or explicitly, as essentially an empirical-inductive enterprise that has four characteristics:

1. Science has achieved a superior kind of truth;
2. Science is characterized by inexorable progress;
3. Science is in the possession of the only method of interrogating nature, namely the empirical-inductive method (the scientific method);
4. This method can be simply described and easily taught.

In the physics text which Stinner as a fledgling high school science teacher used (Eubank, 1963), we find the following steps of the scientific method presented to the student:

1. There is a question or a problem:
2. Collect all the facts about the problem:

3. Propose a theory or possible explanation;
4. Test the theory with an experiment.

Historians of science, however, generally believe that in scientific discovery there is a spectrum of scientific involvement that ranges from identifiable mechanical procedures to high-grade activities involving the educated scientific imagination of the research scientist that cannot be captured by any "scientific method".

To lay the groundwork that will guide our proposed discussion, we will follow the arguments of scientists and historians of science, especially those of Freeman Dyson (1958), and Thomas Kuhn (1964). Putting these ideas together, we propose a framework or model (see Table 1) that replaces the old "scientific method" and allows us to investigate the role played by well-known surprises in scientific thinking.

As early as 1958, in an article in *Scientific American*, Dyson wrote:

> The reason why new concepts in any branch of science are hard to grasp is always the same: contemporary scientists try to picture the new concept in terms of ideas which existed before.

Clearly, Dyson (1958) anticipates Kuhn's notion of incommensurability (1964) and the accompanying "new way of seeing" which produces a new language of discourse for those who are working with the new paradigm. The appearance of a new concept or theory in science, then, is often accompanied by a language barrier. This barrier can be daunting and sometimes difficult to overcome for the science student as well as the scientist. If there is no specifiable scientific method that can be taught, then how can we describe what scientists do?

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One way to show that the so-called "scientific method" as described in many science textbooks gives a very limited picture of scientific thinking is to present a number of "case studies" that involve well-known surprises in the history of science.

We argue that we should picture scientific thinking along a spectrum of activities, which can be described. The complexity of scientific activity entails a process, better described as a continuous *spectrum of activities on three levels*. These activities are seen to ascend from specifiable mechanical procedures that can be learned, to those scientific activities that working scientists normally engage in, and finally to the high-grade scientific activity of a few who finally resolve the puzzle that the surprise presented. (See Table 1.)

According to Kuhn, the need to abandon a research tradition in favour of a new one is signaled by the accumulation of long-standing problems. These unyielding problems, called *anomalies* by Kuhn, do not allow solutions based on the research methods of old traditions, however cleverly applied by the most skillful normal scientists or puzzle solvers. Eventually, one scientist's idea, based on a new set of experiments or observations, metaphysical assumptions and new methods of solution, wins the allegiance of most other scientists. What counted as scientific knowledge in the old tradition is re-conceived, re-evaluated, and sometimes discarded: the scientist now "sees the world differently". Not surprisingly, the new way of seeing, based on the new paradigm, produces a new language of discourse.

**TABLE 1**

**SCIENTIFIC METHODOLOGY SPECTRUM**

(based on Kuhn's work (1964))

| **Specifiable mechanical procedures** | **Scientific activities of "normal" science** | **High-grade activity of scientists working on the "edge" of a paradigm** (this activity cannot be captured by "method") |
|---|---|---|
| Ability to use traditional scientific instruments to make measurements, carrying out testing procedures, making observations, etc.<br><br>These procedures can be complex but they can be taught.<br><br>Note: Even the more sophisticated methods of obtaining data from instruments and many of the interpretations of these data can be taught and then done routinely.<br><br>However, the judgment of whether or not the data fit the requirements of the paradigm must be made by the scientist. | In this region of activity trained scientists are involved Their activities mainly involve the "mopping up operations performed within the confines of a paradigm":<br>a) increasing the precision of agreement between observations and calculations based on the paradigm;<br><br>b) determining the values of universal constants,<br><br>c) formulating quantitative laws in order to extend the articulation of the paradigm; and<br><br>d) deciding which alternative ways to apply the paradigm to new areas of interest is most satisfactory.<br><br>Normal science then is an activity that spans the range from involving specifiable mechanical procedures to | In this region of high grade activity a new way of seeing is required, what Kuhn would label as a new paradigm .<br><br>This also refers to new instruments to be used or unexpected experiments or observations.<br><br>This activity produces a new language of discourse. Scientists, who have grown up with the old paradigm find it difficult to communicate with the young generation who have been converted to a new way of understanding. |

| | | |
|---|---|---|
| | complex but traditional scientific judgments. . | |

Kuhn does not distinguish between what he labels an *anomaly* and what we call a scientific *surprise*. A scientific surprise such as the ones we are discussing we distinguish from what Kuhn labels an anomaly. A Kuhnian anomaly appears as part of the research conducted, but a scientific surprise in the sense of Oersted's, Fraunhofer's and Mendel's discoveries appeared unexpectedly from outside the research program. This notion of scientific surprise also includes, for us, newer theories and the idea that offshoots of experiments and experimental programs can have a "life of their own" within the scientific process .

To conclude this introduction, it is necessary to mention some general factors that are involved in the resistance to and rejection of the importance of a surprise such as the kind we speak of. The scientist-historian Ernest B. Hook has summarized these in his book,

1. Scientists are unaware of it.
2. Having reviewed it, they judge it to be of no immediate relevance to their current work and therefore ignore it.
3. They harbor an inappropriate prejudice against some aspect of the claim.
4. The claim appears to clash directly with their observation or experience – for instance, it is based on an experimental finding they cannot reproduce.

Each of the four presenters will concentrate on one well-known surprise in physical science, in astronomy, in biology, and finally in modern physics/cosmology. First, Stinner will describe the role that surprise played in establishing a new theory in electromagnetism based on Oersted's famous discovery. Then, Teichmann will tell the story of the famous discovery of the dark lines of the spectrum of the sun by Fraunhofer and why this discovery was not accepted as an astronomical research program until much later in the work of Kirchhoff and Bunsen, who laid the ground work for modern spectroscopy. McMillan will discuss the story of Mendel's discovery of the basic laws of heredity, arguably one of the best-known surprises in the history of science. Finally, Winchester will discuss the two greatest surprises in physics and cosmology today, namely *dark matter* and *dark energy*.

**Oersted: An electric current produces a magnetic field**

Although his scientific achievements are well-known today, it took a long time for Hans Christian Oersted to secure a chair in physics at the university level. He was actually refused a position in 1803 because of his “strong interest in philosophy” which was seen at the time as a detriment to the education of a physicist. Being well-to-do, he travelled a great deal and studied with natural philosophers on his own. In Germany, he was impressed by the ideas of the philosopher Schelling who believed that “nature is systematic and unified”. He also met J.W. Ritter who also had similar ideas about the unity of nature, but also emphasized an empirical approach. The dynamic relationship between philosophy, intuition and empirical evidence turned out, in the end, to be the key to his success in physics, even though it delayed his finding a physics teaching position.

Most textbooks present Oersted’s famous surprise discovery in the following way. During the presentation of a lecture at the University of Copenhagen on April 21, 1820, Oersted made an unexpected discovery. As he was setting up his materials to test the heating effect of an electric current on a thin platinum wire, he noticed that a compass needle deflected from magnetic north when the electric current from the battery he was using was switched off and on. This deflection, according to many textbooks, convinced him that a magnetic field radiates from all sides of a wire carrying an electric current, just as light and heat do. He was then able to show, they say, that there was a direct relationship between electricity and magnetism, and then they explain it.

In actual fact, however, the story is somewhat different. Was the discovery an accident (as some of the students attending the lecture claimed) or did Oersted deliberately test the relationship? Students claimed that he was only interested in the heat generated by thin platinum wire and a compass needle just happened to lie in the vicinity of the wire. The effect of the electric current on the compass at first apparently confused Oersted.

On the one hand, he was aware that both Ampere and Thomas Young believed that electricity and magnetism were different phenomena. On the other hand, he also knew that seamen observed that the magnetic needle of a compass was affected when ships were struck by lightning.

After three months, Oersted returned to a consideration of the surprise discovery. In his notes of the time he wrote about the April 20 experience:

> I called attention to the variation of the magnetic needle during a thunderstorm. And I set forth the conjecture that an electric discharge could act on a magnetic needle placed outside the galvanic circuit. Since I expected the greatest effect from a discharge associated with incandescence, I inserted in the circuit a very fine platinum wire above the place where the needle was located. The effect was certainly unmistakable but it seemed to me so confused that I postponed further investigations.

When he investigated the phenomenon three months later he found that the wire carrying an electric current affected a magnetic needle located below the wire by causing it to swerve to a position perpendicular to the wire. His initial interpretation was that magnetic effects radiate from all sides of a wire carrying an electric current, as do light and heat. He thought that the force he observed was an attraction of some sort. But he soon realized that this force was not a Newtonian force. It should be noted at this point that the current produced by a voltaic cell is very small. I am estimating that 10 voltaic cells, or a Voltaic Pile (of the type available to Oersted) would produce a current of about .1 A. In my own demonstrations of the Oersted experiment I found that you need at least a current of 1 A to show the effect on a nearby compass.

His discovery of the complex magnetic effect of electrical current in 1820 was immediately recognized as an epoch-making advance in our understanding of the relationship between magnetism and electricity. Ørsted also discovered that not only is a magnetic needle deflected by the electric current, but that the live electric wire is also deflected in a magnetic field,

André-Marie Ampère quickly repeated Oersted's experiment, and measured the force between two parallel conducting wires. By 1821 Michael Faraday demonstrated the electric motor principle with his rotating magnet experiment. But not until 1831 did Faraday demonstrates the electromagnetic induction principle. Why did it take 10 years to show that a magnetic field can produce an electric current?

## Electromagnetic theory after Oersted

In order to answer the above question more fully, I will suggest that the evolution of our understanding of electromagnetism follows well defined ‘levels of symmetry’. The first level was based on the question: “Is electricity (static and current electricity) related to magnetism, and if so then how can we discover this?” Oersted discovered this relationship and was later more thoroughly investigated by Ampere, Faraday and others. The second level was based on the question: “If an electric current (flow of charge) can produce a magnetic field, can a magnetic field produce an electric field (current)? “ This question was answered about 10 years later by Faraday. He showed that a magnetic field will indeed produce and electric effect, but *only if the magnetic field strength is made to vary in a periodic way*. The third level of symmetry was based on the question:”If the four equations of Maxwell describe all electromagnetic phenomena why are the last two not symmetrical?”

Maxwell himself answered that question by assuming that there is a displacement current in the equation based on Ampere’s law. Finally, the forth level of symmetry is based on the question Einstein asked in the first paragraph of his famous paper on STR: “In the classic Faraday demonstration of producing an electric current by having a magnet move into a solenoid or a solenoid move over the magnet there is an obvious asymmetry, described by two different e-m laws. Why is this?”

Einstein argued that his STR could deal with this asymmetry and showed the reason why only the relative motion in this demonstration counts.

Clearly we cannot discuss these levels of symmetry with high school students beyond the first two. However, physics teachers should be encouraged to study all four levels so that they can elaborate on these in a senior high school physics class and thus make this important topic more interesting.

## Implications for the science classroom

The story of the transition from static to current electricity, from the electrostatics of the early $18^{th}$ century to the development of the voltaic cell by 1800, is not well told in textbooks.

Ideally, before presenting the Oersted effect on a compass, one should discuss the confrontation between Galvani and Volta which lasted about 20 years and gave Volta the idea of a battery based on the work of Galvani with animal electricity. Volta finally decided that there was only one kind of electricity, rather than the three kinds (static, lightning and body) proposed by Galvani. Primitive voltaic cells can be made and tested for the presence of electric current, using a voltmeter. (Of course, Volta could not test for presence of an electric current this way, there were no galvanometers or voltmeters until about 30 years later). Instead, he used sensitive electroscopes. Students seem to accept the explanation that the 20 year delay between the Voltaic cell and the discovery of Oersted was hindered by two factors: a large current had to exist and that the magnetic force turned out to be non-Newtonian force.

Fraunhofer: A new Landscape of the Invisible - dark lines in the spectrum of the stars.

The discovery of dark lines in the spectrum of the sun as well as in some fixed stars since 1802 by William Hyde Wollaston, Joseph Fraunhofer and Johann Lamont radically changed our understanding of the physics of the macrocosm, - of course only in small steps and after about 1859.

Wollaston's simple representation of sun's spectrum, from 1802, can be seen as a simplification and reduction of the phenomenon by way of a seemingly clear connection to contemporary knowledge. On the other hand, Fraunhofer's famous colour copper plate, from about 1817, of the dark lines can be regarded as a meticulous and painstaking representation of the known facts, taken to a high aesthetic level. Finally, Lamont's spectra of the fixed stars, in 1836, can be regarded as the first sketches of these phenomena.

What was common to all of these representations was the general belief that something new and unimaginable could now be established as a scientific subject. These observations also met remarkable interest at other cultural sectors, as for example in Alexander Humbold's understanding of nature and in Johann von Goethe's theory of light and his interest in pictorial representations of nature.

**The visible and invisible sky – a new visual culture is born**

Fraunhofer's hand-made copper etching depicting the dark lines of the sun's spectrum is certainly well known to students, scientists and historians. There are two coloured examples at the Deutsches Museum in Munich, another one at the Goethe *Nationalmuseum* in Weimar. In the publications of Fraunhofer in different journals since 1817 there are only black and white pictures.

It could be argued that Fraunhofer's coloured spectrum – with about 350 painstakingly represented lines - has attained an almost metaphoric significance for the beginning of the modern period of astrophysics that emerged after 1859. Nothing similar can be claimed for the effect made by the scanty drawings of a few dark lines of Wollaston in 1802. In making such a comparison we should include the unpublished sketches of spectra of the fixed stars by Lamont, made in 1836.

For all those (and other) pictures of the sky we use the term "landscape", as an extension of the concept, which Alexander von Humboldt defined in a geo-morphological and metaphoric way at the beginning of the 19.C. e.g. he looked at and admired "the gracefulness of the landscape of the whole firmament" unfold, or when he contemplated "the picturesque effect of the landscape of the milky way". Those concepts are part of his philosophical intentions to offer a "descriptive painting of nature".

But with the spectra of stars there started a totally new- almost abstract- "landscape" of the sky. This was the main reason, why it needed more than 40 years until this "landscape" became accepted by astronomers. This happened after 1859, when Gustav Robert Kirchhoff had explained these strange dark lines by absorption as an analogy to emission in the also strange bright lines from flame spectra.

Fraunhofer in the 1820s became world famous -but not because of his dark lines. He made the best telescopes of his time. E.g. his largest telescope, a refractor, was placed 1824 in the Salvatorkirche in Munich for 8 days long for public viewing. This large telescope was designated for the observatory at Dorpat (today Tartu, Estland) in Russia. The public viewed this display of technical and artistic achievement with great mystical awe. People realized that they were looking at the world's largest refractive telescope - to which was attached a number of other remarkable innovations, for example, a very precise and continuously running clockwork, to move the instrument against the earth`s rotation.

On the other hand, in the "romantic period", the telescope often became a metaphor for all invisible power, that is foreign and destructive, as portrayed by the German poet E.T.A Hoffmann in 1822 in his novel "Meister Floh". Here we witness a confrontation between the two magicians Leuwenhoek and Swammerdam (the two famous early scientists from the history of microscopy) as they argued, using two telescopes, representing swords.

The scientifically educated romantic poet Novalis, around 1800, used the metaphoric concept of the telescope more in a positive way, as a "revelation of a higher world". To both interpretations, the positive and the negative, it was clear that the telescope was a specific instrument to penetrate the invisible.

To sum up, we can say about the poetic reflection of the telescope in the German literature of Romantic to Biedermeier: The telescope becomes "an apparatus for producing a (new) reality for the individual". It is no longer the instrument for the discoveries of an admirable objective sky as a work of God, like it was in Barock era. Now the invisible sky was changed to self-examination and deep reflection of man's relation to the universe.

In 1853 the astronomer Johann Heinrich von Maedler speaks explicitly of a new "Astronomy of the Invisible", but by that he clearly does not understand the curious pictures of the spectrum of the sun, or even spectra of fixed stars, but the potential discovery of new planets, for example the planet Neptune or a companion of Sirius. These discoveries were made by way of exact calculation of the gravitational effect of the neighbouring celestial objects. But this was not principally new. Similar predictions based on celestial mechanics existed much earlier, for example with the prediction of the return of Halley's comet in 1759. Maedler's "objects" also belonged to the landscape of "positional astronomy". Positional astronomy was the essential condition for the exact predictions of celestial mechanics. All its objects testified to a sublime aspect of the verified sky that connects us to the order and law-likeness that is mirrored by nature – completely in contrast to the chaotic dark lines of Fraunhofer as first presented in 1817.

Positional astronomy meant that only points of light and their position and movement were officially recognized as scientifically important objects that can be exactly observed, and – at least of planets and double stars – where the motion and position can be exactly calculated using the power of the newly developed celestial mechanics (from Euler to Gauss). Even the colour of the celestial objects was irrelevant!

The new science of spectral analysis (which began in 1859) that now used the not-yet well understood "landscape" of spectral lines as a symbolic language, did not render classical positional astronomy obsolete. Not surprisingly, it severely limited the importance of positional astronomy progressively more and more after about 1900 by extending the new landscape of the spectral method. It showed and classified many different identifiable spectra of stars (and other objects in the sky such as nebulae), but were not understood in detail until about 30 years later with the advent of atomic physics (1910-1926) and modern quantum mechanics, after 1926. Photography and the use of diffraction gratings, after about 1880 aided in identification of star spectra by allowing the comparison of lines be made easier.

The first extensive classification of star spectra as pictures of a really new astronomy already existed around 1890 featuring about 10000 photographs of star spectra. By 1918 this number grew to over 200

000. Until the 1940s difficult spectra of giant stars and white dwarf stars were now classified according to their spectral impressions as “pictures”.

This new astronomy revealed the physical and chemical structure of the luminous celestial objects. Using spectra it was now possible to place stars on the laboratory table of the astronomer. This went far beyond the expectations of most astronomers. Admittedly the strict requirement of precision and accuracy of positional astronomy had to be sacrificed. As late as 1950 the calculations of the amount of chemical elements in stars, taken from the spectra, could be wrong by as much as 100 to 200%! As late as 2002 one could find in publications inaccuracies as high as 50%. Around 1960 only 18 chemical elements at the sun, together with less than 300 Fraunhofer lines had been quantitatively identified to an exact amount. Every astronomer of the $19^{th}$ century would have refused to recognize such results as science.

This was the second big problem for accepting the new "landscape" of the Fraunhofer lines before 1859 and even for many classical observatories, until about 1900. The “landscape” seemed to look too chaotic for 19th century astronomers who believed to remain on the top of all exact sciences.

**Implications for the science classroom**

It is difficult even to see a scientific problem, if the phenomenon studied is totally different from all familiar knowledge. This is the first thing that should be made clear using examples of scientific surprises like those we presented here. The teacher may start by showing the drawings/(copper etches) by Wollaston, Fraunhofer and Lamont and ask what students think, how this phenomenon can be related to the physics and chemistry of stars (students today are familiar with bar codes in shops, also those of DNA research). In addition, the teacher can add some information about the Morse code of telegraphy, that was invented in the $19^{th}$ century. Finally, it should be emphasized that what was known in the first half of the $19^{th}$ century about the sun and stars: almost nothing. Even the great astronomer W.Herschel (around 1800) believed that sunspots were holes in the hot luminous atmosphere of the sun, which suggested , that under the solar atmosphere there was a cool surface.

Continuing the story, students should be shown examples of star charts: Only light points were interesting. Now we can ask students: how would it be possible to become interested in such chaotic "bar codes" of stars, which at this time was an unsolvable puzzle. Now the teacher can tell that the "bar code" of the sun at least was very helpful in optical technology (for finding exact values for refraction and dispersion). Moreover, astronomers were by no means interested in physics or chemistry. They remained an arrogant species of scientists, who alone believed to know, what exact science should be. To end the lesson students are asked: Are there any analogous situations in modern developments in science/technology?

## Mendel in School Science

If students learn about Johann Gregor Mendel, and not simply his name or that he is known as "the Father of Genetics", this learning either occurs in the context of heredity and patterns of inheritance or as an introduction to classical genetics before a study of the molecular basis of inheritance and how genes control metabolism. In Canada, these topics generally follow a study of the cell in Grade 8 General Science and a study of the cell cycle (mitosis and cytokinesis), asexual and sexual reproduction, and the formation of sperm cells and ova by meiosis in a Grade 9 General Science reproduction unit.. If the learning focused less on knowing and applying science knowledge and more on how this knowledge came to be constructed, through experimentation followed by analysis and interpretation of experimental data, students would have opportunities to work and think like scientists and to recognize, first-hand, that "the scientific method" poorly captures what is involved in scientific discovery, particularly surprise discoveries like Mendel's.

### Breeding Garden Peas

According to Mendel's biographer Iltis (1932) and Henig (2000), Mendel's scientific and personal papers were burned in a bonfire set in the monastery courtyard soon after his death on Saturday, January 6, 1884. What remains are Mendel's two papers on plant hybridization and nine papers on meteorology published in the journal of the Brünn Society for the Study of Natural Science between 1836 and 1871 (Orel, 1984. Unlike Charles Darwin of the same era, very little specific information about Mendel exists, and this includes the detailed notes and meticulous records he must have made during his eight years of research breeding the garden pea, *Pisum*. Even with access to the two papers on plant hybridization published by the Brünn Society as the monograph, *Versuche uber Pflanzen-Hybriden* in 1866, Henig claims:

> We can only speculate about what really happened. We do not know exactly how the experiments were done, in what order, during which seasons, even precisely where in the wide courtyard of the St. Thomas monastery in Brunn. We do not know for sure how many generations Mendel squeezed into a single growing season, nor how often he grew plants in the greenhouse and how often in the garden. (2000, pp. 130-131)

There are also questions about Mendel's reasons for beginning these experiments in 1854. Henig speculates that Mendel's *Pisum* experiments began after Mendel failed the oral examination that would have qualified him for a career as a high school teacher. Eduard Fenzl, director of the Vienna Botanical

Gardens and member of Mendel's examining committee, was a spermist; he believed that the preformed plant embryo resided in the pollen and passed into the ovary through the pollen tube. Mendel, in contrast, believed the embryo formed at fertilization with equal contributions from the male and the female. Fenzl was the first to question Mendel and asked about generation. According to Henig, Fenzl disagreed with Mendel's answer and an argument ensued. Rather than back down, Mendel chose "failure over capitulation" and walked out of the examination knowing he had a battle to resolve (2000, pp. 62).

In the minutes of an 1837 meeting of this society, Napp is reported as saying, "The question for discussion should not be the theory and process of breeding, but *what* is inherited and *how*?" It was Mendel, Mawer states, who took up Abbot Napp's challenge (2006, p. 51). Mendel's introductory remarks[1] in Unger's Unger's mechanistic and hard science view of botany helped Mendel to regard the development of living things as being directed by physical and chemical laws (Corcos & Monaghan, 1993). Experimental physicists Christian Doppler, Andreas von Baumgartner, and Andreas von Ettinghausen exposed Mendel to the mathematical analysis of physical problems and statistical knowledge (Olby, 1966), through Ettinghausen's combination theory and his lectures on combinatorial analysis – "the mathematics of probability and outcome" (Mawer, 2006, p, 53). Mendel came to understand that all phenomena were governed by laws, "that the laws of nature were written in the language of mathematics", and the task of a scientist was "to reveal these laws and create theories, experimentally proved" (Orel, 1984, p. 30).

In the spring of 1856, Mendel began his experiments, and it is at this point that he devised a strategy for experimentation that was considered "more effective" than those of all of his predecessors. Rather than look at the "difficult, complex and messy" whole, Mendel – "with the scientific outlook of that of an ultimate reductionist," focused on one trait at a time (Ibid.). He wrote: "The object of the experiment was to observe these variations in the case of each pair of differentiating characters, and to deduce the law according to which they appear in successive generations (Mendel, 1950, p. 4). Roberts (1929) described this as "pitting one character in an individual against a single *contrasting character* in another individual" and from his perspective this decision "revealed Mendel's scientific genius and analytical insight" (p. 293).

In rows specific to one type of a contrasting trait, Mendel planted the seeds from the pairs of seven traits in his garden plot. When the flowers for each pair of a specific trait developed, yet were immature, he removed the anthers within each flower from one of the two types before they had time to produce pollen.

As one example, he removed the anthers from the plants that would be producing seeds with a white coat, but left intact the anthers in the flowers of the plants that would be producing seeds with a grey coat. Hethen used a camel hair brush to transfer pollen from the intact anthers to the stigmas of the emasculated flowers. Using the previous example, the plants that would through self-fertilization have created seeds with white coats, had been cross-fertilized with pollen from plants that through self-fertilization would have created seeds with grey coats. For each pair of contrasting traits, Mendel carried out from 23 to 60 (mean of 39) cross-fertilizations on an average of 10 emasculated plants or 287 fertilization on a total of 70 plants (Mendel, 1950, p, 6). He named this the

At the end of this first season, Mendel collected the seeds, labeled and dried them, and stored them until the following spring of 1857 when they would be planted and grown to maturity. In this first hybrid generation [$F_1$], Mendel observed in each of the seven crosses, "the hybrid-character resembles that of one of the parental forms so closely that the other either escapes observation completely or cannot be detected with certainty" (Mendel, 1950, pp. 7-8). He labeled those traits that "pass into the hybrid association entirely or almost entirely unchanged, thus themselves representing the traits of the hybrid…dominating" and those traits "that become latent in the association, recessive" (Corcos & Monaghan, 1993, p. 77). For the seven contrasting traits, the following were determined to be dominant: round seed, yellow seed albumin [cotyledon], grey seed coat, inflated pod, green pod, axial flowers, and longer stem. With this experiment, Mendel also confirmed an observation that Gartner had made about the source of the dominant trait in the hybrid and the form of the hybrid being identical whether the source was the seed bearer or the pollen parent (Ibid., p. 8). He also "meticulously noted" a stem condition that today is know as hybrid vigor; hybrids can have a greater height that the parental lines (Mewar, 2006, p. 57)).

The generation bred from the [$F_1$] hybrids, whether through self-fertilization or reciprocal crosses, showed that these hybrids had not breed true even though the trait shown in each case had been the dominating one. The [$F_1$] hybrids had to be variable because their offspring were not all like the parents. Regardless of which of the seven traits Mendel studied (see Table 1 below), he found "that among each four plants of this [$F_2$] generation three receive the dominating and one the recessive characteristic" (Corcos & Monaghan, 1993, p. 82). Moreover, when Mendel collated the results of the all $F_2$ experiments, he found that the average ratio between the dominating trait and those with the recessive trait was also 2.98:1, or 3:1.

Table 1: Results from the $F_2$ Generation

| Trait/Character | Total | Dominating | Recessive | Ratio |
|---|---|---|---|---|
| Seeds | | | | |
| Shape of Seed | 7324 | 5474 | 1850 | 2.96:1 |
| Colour of Seed | 8023 | 6022 | 2001 | 3.01:1 |
| Whole Parts | | | | |
| Colour of Seed Coat | 929 | 705 | 224 | 3.15:1 |
| Shape of Pod | 1181 | 882 | 299 | 2.95:1 |
| Colour of Pod | 580 | 428 | 152 | 2.82:1 |
| Flower Position | 858 | 651 | 207 | 3.14:1 |
| Height of Plant | 1064 | 787 | 277 | 2.84:1 |

Three items related to this experiment are of particular interest. First, Mendel mentions that he did not observe any transitional forms. This suggests that whatever the heritable factor for the recessive trait might be, it had not been diluted in any way by co-existing with the dominating factor in the [$F_1$] hybrids. Second, Mendel recognized that the dominating traits have what he called "double significance" (a true-breeding parental form vs. a hybrid form). As such, even though the parental and hybrid dominating traits had the same appearance, they did not behave in the same way and the only means of determining in which from the dominating trait exists would be to examine the next generation produced by self-fertilization. This would be the experiment he carried out in 1859. Third, Mendel reduced the thousands of seeds he had sorted and then counted to the whole number 3:1 ratio. Corcos & Monaghan (1993) suggest that Mendel was the first person to adapt and apply ideas and methods from the physical science to biology.

At this point in time, Mendel began to denote the pure breeding dominating trait as "A", the pure breeding recessive trait as "a", and the hybrid as "Aa". He also began a series of two-trait hybrid crosses and three-trait hybrid crosses. These experiments led to two results that will be mentioned here. The first, was Mendel's claim that "the relation of each pair of different characters in hybrid union is independent of the other differences in the two original parental stocks" (Ibid., p. 19). Although we now realize that it is not true for all cases, Mendel recognized that the traits he was focusing upon in *Pisum* were inherited independently of other pairs of traits. Not surprisingly, his work with such multi-trait hybrid crosses led to an interest in discovering whether the experimental results (the products of all combinations of possible hybrid traits) would match the combination series he could generate by knowing the number of each pair of differing traits (Ibid.). Mawer (2006) claims "the real significance of this finding [which Mendel verified could be and actually was accomplished] was missed", even in 1900. It represented "precisely the inherited variation that Darwin needed to make his theory of natural selection work" (p. 62).

One of the final topics that Mendel addressed in *Experiments in Plant Hybridization* was his study of the reproductive cells of the *Pisum* hybrids. It is Mendel's comments on "fertilizing cells" and "potentially formative elements" in "Concluding Remarks" to which Stent (2002b) has gone to illustrate Mendel's mention, albeit implicitly, of the particulate nature of heredity. This is also a section (Mendel, 1950, p. 35-36) about which Mawer writes, "…Gregor Mendel was shining a light into the darkness ahead: he had actually understood how inheritance worked. His tragedy was that there was no one to step forward with him" (2006, p.67)

## Dark matter and Dark Energy: contemporary surprises in science

Of the unexpected developments in astronomy and physics, perhaps none is more unexpected or more puzzling than the discovery that if our general theories of gravitation are more or less right then there must be much more matter and much more energy in the universe that surrounds us than can be seen through electromagnetic interactions and their detection.

The first person to notice this was Fritz Zwicky, a Swiss national, who was working at the University of California, Berkeley in 1934 when he discovered that in order to account for "missing mass" in orbital clusters of galaxies he had to postulate a source of non-visible (or non-electromagnetic) mass which he termed "dark matter". Although his work was neglected for a long time a number of other developments astronomically have pointed to the same conclusion, namely, that a great deal of the mass of the universe is not within the electromagnetic realm but is purely gravitational.

Subsequently observations of variety of kinds has suggested that not only is the universe not stable, but is in fact expanding at an accelerating rate. The main kind of evidence for this is connected with Hubble's law that the farther away a star system or galactic cluster is from the earth the faster the star system or cluster is moving relative to us. Careful measurements by a joint Harvard/Berkeley team looking at thousands of galaxies near a new moon and some weeks later when they could identify supernovae as they were starting to brighten. Following the light variation using ground and space-based telescopes they found that the form of Hubble's law for the expansion speed of the distant supernovae versus their distance curved upwards confirms the view that the expansion of the universe is accelerating.

In order to account for this apparently convincing conclusion there has been a return to Zwicky's "dark matter and its closely analogous "dark energy" as postulated entities that cannot be detected directly as we can stars and galaxies using electromagnetic phenomena with our various kinds of telescopes. (Because of the Einstein equivalence of matter and energy, E = mc2 one has to recognize a gravitational effect of energy as well even when it does not appear in a mass-like form.) As it happens, the dark energy component of interstellar space appears to make up about about 72% of the gravitating material and dark matter another 23% leaving only roughly 5% for the stars, planets and ordinary matter.

In 1996 a large cosmology conference in Princeton arrived, by a peculiar process of competition and consensus, at the view that Michael Turner's "Lambda-CDM" model gave the best account of these experimental results. (Lambda is just the Greek letter for Einstein's cosmological constant and CDM is "cold dark matter".) (See Critical Dialogues in Cosmology, ed. N. Turok, World Scientific, Singapore (1997) where the proceedings are published.) Essentially the model reinstates Einstein's old cosmological constant as an anti-gravitational effect with the assumption that the expansion of the universe is very close to the critical rate as predicted by inflationary theories. It includes a tiny positive value for the cosmological constant that can be tweaked to match the measured data for expansion rate. The peculiarity is that this constant is of the order of 1/10 to the 120th power, or as near to zero as can be without actually being zero. (Other considerations deriving from quantum mechanics of fundamental particles tends to conclude that this ought to be not a number very near zero, but identically 1. This difference is one of the deepest puzzles in contemporary physics and is awaiting its Einstein.)

When Einstein initially formulated his general theory of relativity, that is to say his theory of gravitation, he initially included a constant (the so called cosmological constant) in his equations so that the universe would be stable. He soon abandoned it considering it one of his major blunders. But in recent years something like his cosmological constant has reappeared in the thinking of many physicists who are tackling the puzzles surrounding dark energy and dark matter.

The peculiar situation as we have it today is that the visible universe, which is likely to be a tiny part of an exceedingly diverse "multiverse", is accelerating along lines suggested by George Lemaitre more than eighty years ago. This acceleration is well described by adding to Einstein's equations a cosmological constant of the kind that Einstein originally introduced and then abandoned which we now interpret as the "vacuum energy" of the universe, following Lemaitre's initial suggestions in 1934. The resulting picture of the universe has, as mentioned before,72% of its energy density in this gravitationally repulsive vacuum form and the remaining 28% or so in forms of dark and luminous gravitationally attractive matter.

This accelerating universe appears to have some peculiar properties. For example if it continues an accelerated expansion as it is presently doing there will come a time that star formation and galaxy formation will cease since the universe will be expanding at a rate too great for any physical processes to keep up. Thus the future is likely to be one of dead stars and isolated elementary particles. There will be a horizon beyond which any observer or any device designed to observe will be unable to see.

This also leads to the conclusion that at some point in this future expansion if stars and galaxies cannot form then carbon based life or any other imaginable kinds of life will also be unable to form. The conscious universe will no longer be a possibility and the universe will no longer know of its own existence as it does now. "Once was the time of Man", the old 1960's refrain, will have a point.

**Implications for the physics classroom.**

Students today are very interested in modern physics, especially as it relates to astronomy and cosmology. They may be familiar with the Bohr model of the atom and even with the rules used to describe the electron structure of an atom based on the Schroedinger version. If the teacher has good understanding of the basic ideas of Einstein's theory of relativity, they may even learn the basic assumptions and testable consequences of both the special and general relativity. The physics teacher should have sufficient background knowledge as well as the an ability to discuss the phenomena of dark energy and dark mass, along the lines discussed. The teacher should be able to discuss Zwicky's work by simply calculating the collective motion of stars in a galaxy, using Newton's laws of motion and the inverse square law of gravity. Hubble's law is easily understood since it is simply a linear relation. To make sense of the expanding universe the acceleration can be compared with a rocket leaving earth with the escape velocity of abou11 km/s. If the rocket is found later to accelerate after all power is turned off one has to postulate a mysterious force pushing it. Fascinating stuff for high school students.

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## Appendix 1

# The Terminology of Science

**Assumption**:an assertion taken to be true without verification. The postulates in Euclidian geometry are assumptions upon which Euclidian geometric proofs are based.

**Data**: records resulting from observations. Note that data is the plural of datum. A specific item of data is sometimes referred to as an observation.

**Deductive process**: the logical process in which a law or principle is applied to a specific case. A prediction such as The wind is blowing from the southwest, therefor it will rain is the result of a deductive reasoning process and could be used as a hypothesis to test a law stating that When the wind blows from the southwest, it will rain. Deductive reasoning is based on a premise which is assumed to be true for the purpose of making the deduction. Inferring is a related term. The popular phraseology for deductive processes is reasoning from the general to the specific.

**Hypothesis**: a conjecture or prediction made by reasoning deductively from a theory or a law. Contrary to what is implied by many high school textbooks, hypotheses are not simply guesses but are predictions about the results of experiments or observations arrived at deductively. Hypotheses cab be thought of are logical consequences of theories.

A common misconception is that hypotheses, theories and laws or principles are on a continuum of certainty along which hypotheses become theories and theories, when firmly established become laws. This is not the case, theories are quite something else. Hypotheses never become theories; theories never become principles.

**Inductive process**: the logical process resulting in the identification of a regularity or pattern in a set of observations. For example, noting that it always rains when the wind is blowing from the southwest after observing local weather patterns for a period of time is an inductive process. The popular phraseology is reasoning from the specific to the general.

**Scientific law (principle)**: statement resulting from scientific inquiry that describes a relationship among twoor more natural phenomena. Since scientific laws are expected to apply in all cases in which a given set of conditions prevail, they are often referred to as generalizations. Scientific laws may be either quantitative or non-quantitative (qualitative). For example, Charles' Law which describes the relationship between the temperature of gases may be stated non-quantitatively as:

*At constant pressure, the volume of a gas varies directly with its temperature" or quantitatively: V/T = K where V = the volume of a gas at constant pressure, T = the temperature the gas in Kelvins,, and K = a constant.*

Objections to the term *law* in reference to scientifically observed regularities have been raised because of its connotation of absoluteness. Since the term is so widely used, it seems better to understand its real meaning in the context of science rather than to shun its use.

**Observation**: that which is sensed either directly or indirectly by means of instrumentation. Observations may be naturalistic and unstructured as in the case of a biologist observing the behaviour of a wolf pack or highly structured and with the aid of elaborate instrumentation resulting in a set of numbers or squiggly lines on a chart as might be the case in a chemistry or physics experiment.

**Prediction**: virtually synonymous with hypothesis; the predicted outcome of an experiment or set of naturalistic observations, made on the basis of a theory. A prediction made from the theory of plate tectonics does not necessarily imply prediction of the outcome of an experiment. It could just as well be a prediction of what will be found if one looks in certain places in the earth's crust. Geology is not removed from the realm of science because one cannot make predictions and do experiments with the crustal plates or the rock strata in the earth's crust. By the same token, evolutionary theory does not require that evolutionary changes be predicted and observed in order for the theory to retain its scientific status. Indeed evolutionary theory implies that one would not be able to predict future forms of life even if one could observe the process. This uncertainty is not unique to plate tectonics and evolution, but exists in many aspects of atomic structure and animal behaviour as well.

**Operational definition**: that which is observed in an experiment. Rutherford could not observe alphaparticles directly but he could observe scintillations (flashes of light) on a zinc sulphide screen. The operational definition of an undeflected alpha particle in Rutherford's famous experiment that revealed the structure of the atom was a scintillation on a zinc sulphide screen directly behind the gold target.

Suppose a chemist expects the following the following reaction:

$$\underset{\text{green}}{AX} + B \text{ ------> } A + \underset{\text{blue}}{BX}$$

Since she cannot see the molecules of reactant and product, she can know the reaction has taken place only if something observable such as a colour change is known to accompany the reaction. In this case, the presence of BX could be operationally defined as a colour change.

**Theory**: a conceptualization that explains a class of phenomena. The phenomena which a theory explains arethen interpreted as manifestations of the theory. The ultimate goal of science is the construction of theories.

**Variables**: factors that might affect the outcome of an experiment. In an experiment, relevant variables aredentified and controlled, while one variable, the independent variable, is manipulated to determine its affect on a second variable, the dependent variable.

For example, an experiment is performed to determine the effect of temperature on the pressure of oxygen in a sealed chamber. The temperature is increased gradually while the pressure in the chamber is recorded at regular intervals. In this experiment, temperature is the independent variable and pressure the dependent variable. Since volume also affects pressure, volume is a relevant variable and must be held constant throughout the experiment.

## Appendix 2
## Inductive and Deductive Processes

An understanding of the relationship between ***inductive*** and ***deductive*** reasoning is fundamental to understanding the nature of science.

### *Deductive Processes*

The deductive processes involve deductive reasoning. Deductive reasoning is best through examples. Consider the following simple syllogism:

**Premise 1:** All people are mortal.
**Premise 2:** Madonna is a person.

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**Conclusion:** Madonna is mortal.

If premises 1 and 2 are true, then the conclusion is true, and Madonna is, indeed, mortal. This form of argument is called a ***deductive argument***, and in this case, the conclusion is logically valid (true). Deductive arguments lead to <u>certain conclusions from premises that, for purposes of the syllogism, are considered be true</u>.

But what if the premises of the argument are contrary to fact, that is, not true? Consider the following:

**Premise 1:** All people are immortal.
**Premise 2:** Madonna is a person.

---

**Conclusion:** Madonna is immortal.

If premises 1 and 2 are true, Madonna is immortal. We have arrived at a conclusion that is ***logically true*** but ***empirically false***. It is empirically false because in the "real world", based on empirical (observed) evidence, premise 1 is false. Some who disapprove of Madonna might argue that premise 2 is also false but once again, the evidence at hand supports premise 2. So the implication of our syllogism is that Madonna will live forever.

Let's go back to our first syllogism, "All people are mortal, Madonna is a person, therefore Madonna is mortal" and recast it as a scientific theory. We'll call the two premises principles and taken together call them a theory. Our theory come syllogism now reads:

**Principle 1:** All mammalian bipedal entertainers are mortal. (We don't even have to limit ourselves to human entertainers, we can include entertainers among our cousins, the apes.)

**Principle 2:** Madonna is a mammalian bipedal entertainer.

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**Hypothesis:** Madonna is mortal.

Just as the premises of our syllogism led us to the conclusion that Madonna is mortal, our admittedly, simple-minded theory about mammalian bipedal entertainers, including Madonna, leads us to hypothesize that Madonna is mortal. When we testing our hypothesis we also test our theory. If our hypothesis proves to be false, i.e., Madonna is not mortal, then one or the other or both of our principles is false and our "theory" is false.

If Madonna is mortal, does that prove that all mammalian bipedal entertainers are mortal? In other words, if our hypothesis is true, is our theory necessarily true? Clearly, the answer is no. Our theory could be true but it is not necessarily true, because although Madonna may be mortal but perhaps Michael Jackson is not. And so on.

This raises the interesting question of how many entertainers we would have to examine in order to have total confidence in our theory, an issue discussed further in the section on The Nature of Science in your textbook.

**Inductive Processes**

Inductive reasoning is often referred to as "Reasoning from the specific to the general". As discussed in your text, some philosophers of science (who incidently often times also practising scientists) have asserted that science is essentially an inductive process. If science were truly inductive, scientists would wander around looking at things (or maybe squint through a microscope at them) until they noticed a regularity or pattern and say something like, "Aha! I noticed that all the snails on this beach eat Fucus (brown alga). Therefore, the carbohydrate in Fucus is an essential food for snails."

At the early stages of biology, much research was of this nature. Understanding biological processes and to a lesser, although significant extent chemistry, requires an exhaustive background of "trivial" information. Imagine the amount of data required before one would notice the discontinuities in evolutionary patterns of organisms and propose the theory of punctuated evolution. Indeed, it is unlikely that one would not even look for such a pattern unless one understood the more traditional notions of evolutionary processes.

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## Appendix 4

### Science Stories, taken from the history of science

**The Ionians, and the Greeks**: **Thales to Ptolemy**

-The three *laws of physics* (reputedly discovered by Archimedes) that have essentially remained unchanged: law of the lever, law of flotation, and the law of reflection.

-Archimedes' mathematics, as it applied to his physics. Archimedes' screw, and Archimedes: physics and war machines.

-Determination of the length of the year and the circumference of the earth: Aristarchus, Eratosthenes.

-Plato's cosmological question: "By the assumption of what uniform and ordered motions can the apparent motions of the planets be accounted for?

-Plato's theories about the origin of the universe

-Zeno's paradoxes.

-The experiments of Empedocles; for example, "the water clock experiment", his experiments in optics to test his theories.

-Democritus' atomic theory of matter.

-The three outstanding mathematical problems of the Greeks: the squaring of the circle, the trisecting the angle, and the *Delian* problem.

-Hippocrates and medical science.

-Aristotle's biological studies, his physics and his great experiment: "The embryology of the chick".

-The Ptolemaic solar system.

-Hero's experiments.

**Later Middle Ages to Copernicus**

Young science students are especially well predisposed to consider some of the main scientific concepts as put forth by the natural philosophers of the middle ages. The notions of *impetus* and *mean value* in physics and the application of a simple atomic theory in chemistry are examples of concepts that lend themselves to profitable classroom discussion.

- The concept of *impetus* in the teaching of motion.

-The application of the *mean value theorem* to problems involving average value.

-The optical experiments of Theodoric of Freibourg, especially the experiment to discover the "Causes of the Rainbow".

-"A day in the life of an alchemist."

-Roger Bacon's philosophy of scientific method.

-Medieval optics and theory of light.

-Could medieval physicists have developed a telescope?

-Roger Bacon (13th century), the "new scientific attitude" and the nature of scientific enquiry.

-Thomas Aquinus' attempt to reconcile the scriptures with the physics of Aristotle.

-Robert Grosseteste and scientific enquiry. His discussion of the inductive process deals with the passage from observation to laws anticipates the 17th century scientists' understanding of scientific method.

-Nicolas Oresme anticipated much of Galileo' work on motion.

**Copernicus to Newton**: **The Scientific Revolution**.

The following are examples of topics related to the science of the Renaissance and the seventeenth century that can be developed into teaching units, namely "science stories":

-Copernicus and the geocentric solar system.

-The problem of navigation in the 15th and 16th centuries.

-The Julien calendar: why reform was necessary.

-The problem of finding the longitude at sea.

-Observations of the sky for children.

-The compass and how it changed navigation.

-Mercator and the problem of representing the spherical earth upon a plane map for the purpose of navigation.

-The development of the theodolite and triangulation for determining distances.

- Leonardo da Vinci's mechanical inventions.

-Vesalius and the study of anatomy and physiology.

-Chemistry in the 15th and 16th centuries.
-Galileo's inclined plane experiment.

-Galileo' telescope.

-Robert Hooke and the microscope.

-A day in the life of Robert Hook, FRS.

-Galileo' astronomical observations.

-Newton's mechanical experiments.

-Newton's optical experiments.

-Harvey's theory of the circulation of the blood.

-Roemer's determination of the speed of light.

-Kepler's "War on Mars".

-The *phlogiston theory* in chemistry.

-The confrontation between Priestly and Lavoisier over oxygen.

-Lavoisier's experiments to investigate oxygen.

-Volta's experiments with electric batteries.

-Dalton's assumptions, his observations and his experiments which led to his atomic theory of matter.

-Davy's experiment separating water by an electric current.

-Chemical shorthand: from the alchemists to Dalton and then to Berzelius

- Faraday's electromagnetic experiments.

-Young's experiments to demonstrate the wave nature of light.

-Making a simple spectroscope.

-Determining the distance between two point by triangulation.

-Determining the distance to a star by the parallax method.

-An account and a discussion of Darwin's *The Voyage of the Beagle* as a background to his theory of evolution.

-A discussion and partial replication of Pasteur's experiments to put to rest *spontaneous generation*.

-The evidence for the germ-theory of disease.

-The story of the unit charge in electric phenomena: from Coulomb's measurements, to Faraday's electrochemical experiment to Thompson's discovery of the electron. Do electrons really exist?

-John Tyndall and the *Tyndall Effect*.

-Faraday's lecture on "A Burning Candle".

-Laplace' theory of the origin of the universe.

-Linnaeus' classification: an improvement over Aristotle's?

-The Doppler effect and its use in astronomy.

-The discovery of Neptune: Newton again vindicated.

-Chemistry, Physics and the discovery of photography.