THE ROLE SCIENCE PLAYS IN SCIENCE EDUCATION

by

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For Leo

who served as my model scientist

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ABSTRACT

An image of science has developed within science education that is not shared within science, and teaching methods have emerged that are compatible with this image, but not with science itself. In this century, a gap has opened between science and science education as the influence of scientists diminished, and educational theory has assumed a greater role in school science teaching. New definitions emphasizing science as a system of methods and attitudes rather than a body of knowledge have arisen in the community of educators. These see scientific knowledge as tentative and as the products or conclusions of science rather than an active part of it.

No coherent image of science emerges from the work of scholars. Scientists have had little scholarly input into discussions about science, so their views are poorly understood. They work in a distinct culture that demands specialization. There is a conflict between this culture, with its communal and authoritarian approach to theory, and general Western culture that values the right of every individual to question every decision. Within science, knowledge is valued more than methods, but within education, the processes and attitudes of science are valued more than the knowledge itself.

There is no ideal solution to science teaching, and no teaching method that does not have disadvantages as well as advantages. Science education will be improved only by making small changes, each one a compromise that tries to include the most important features of science but also appeals to the needs of students.

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INTRODUCTION

Science education is influenced by three major forces: students and how they learn, societal pressures, and the scientific disciplines. The relative influence of each of these forces shifts with the times; sometimes scientific disciplines have a greater influence, and sometimes the other forces determine the curriculum and teaching methods. Inevitably, science teaching is a compromise between these factors, and it is important that members of the community other than scientists take part in decisions about science education. However, to understand the *kind* of compromises being made, all those who participate in the decision making need to understand the nature of science. I will focus on the discipline of science, biology in particular, to see what part it plays in science education: how much scientists influence the curriculum, to what extent the curriculum is organized around disciplinary knowledge rather than educational or social issues, and what definition or image of science is being presented to students.

I will examine four major aspects of science education, beginning with a historical account of developments over the last century, in biology, education and science education. Then I will analyse some widely used teaching methods and examine assumptions about science implicit in each teaching method, and the image of science each presents. I will assess recent studies of science by philosophers, sociologists and historians, and integrate this assessment into the analysis of teaching methods. Finally I will examine why science, as an activity is hard to understand, and discuss how we can present science most accurately and whether we should present scientific knowledge as true, tentative, or something in between.

Historical analysis of science education

I begin by summarizing the history of scientific developments in certain areas of biology (evolution, genetics and molecular biology), and the parallel history of ideas in science education, then analyse the relative influence of each of these factors on the curriculum and teaching methods used in the schools. Textbooks written for schools and universities give a picture of what was actually presented, and focusing on Nova Scotian schools gives the actual experiences in one locality.

There have been three periods since 1850 when there were dramatic advances in biology. The first began with Darwin's theory of evolution in 1858. It changed both research and teaching in biology. Scientists looked for evidence of evolutionary relationships and began to form large, encompassing theories that would explain evolution, development and cell structure. The second major change came after 1900 as scientists developed genetics, but also began to form smaller testable hypotheses, and used experiment rather than observation. In the classroom, more importance was placed on function than structure, and increasingly courses centred on explanation of organ systems, like digestion or respiration, rather than on comparative surveys of organisms. The third advance came after 1950 with the opening up of biochemistry, development of the electron microscope, and discovery of the structure of DNA. Life was suddenly better understood at the molecular level. In classrooms the emphasis changed from the differences between organisms, to the principles common to all life, and these principles were taught, not just at the level of the individual organisms, but also at the levels of molecules, cells and populations.

Even though the major advances in evolution, genetics and molecular biology occurred at different times, they were handled, first by researchers and then by educators, in similar ways. Each breakthrough was followed by an initial period of controversy and confusion. In each case the basic concepts were rarely mentioned in textbooks until after they had been accepted by the scientific community. Initially, textbook accounts were detailed and confusing and they varied from author to author. Later, as authors become more comfortable with the concepts, they were able to explain them more efficiently, so the variety of presentation disappeared and explanations become more effective and economical, but less exciting.

In the nineteenth century scientists controlled science education, so the same approaches were used in scientific research and science education. Early in the twentieth century, reform movements drew education away from university control, and a gap developed between science and education; the gap widened over the twentieth century as educational theory played a greater role in school science teaching and the influence of scientists diminished. Increasingly the educators and scientists spoke different languages, and defined important aspects of science differently.

Within education, a process can be traced in which ideas from theories of education were used in theories about science and science education. The project curriculum, popular in the 1920s, was the source of ideas that were slowly integrated into theories about science. New definitions of science, different from those held by scientists, slowly arose within the community of educators. These definitions change the emphasis from science as a body of knowledge to science as a system of methods and approaches.

The methods used to teach science

The modern approaches to science education fall roughly into five categories: problem-solving, inquiry, constructivist, science technology-society (STS) and traditional. Although five approaches are identified, I believe there are really two *solitudes* in science education. On one side are the "modern teachers" and researchers in education who support the newer approaches to science teaching (inquiry, constructivist, STS). They are relativists with respect to scientific knowledge, and they support reduced content, emphasizing scientific methods and attitudes rather than scientific knowledge, increased social relevance for science education, and greater control by students over their own learning. On the other side are the "traditional teachers" who usually teach a larger amount of content, are realists about scientific knowledge, and use a subject centred approach. These teachers are really called "traditional" because they are uncomfortable with the newer methods. "Modern teachers" are critical of "traditional teachers," considering them to be poorly informed, lazy or too conservative to change. There is no voice for traditional teachers in the discussion about science education because they hesitate to admit that they use traditional methods, so they do not argue in favour of them. The name "traditional teacher" is not one they would choose for themselves.

The term "solitudes" is appropriate because these two kinds of teachers do not communicate effectively with each other. They do not recognize how their perspectives differ, and they do not identify the premises on which their teaching methods are really based. I believe the "traditional method" is grounded in science and in practice, while "modern methods" are grounded in educational theory. I will try to identify the hidden premises behind the arguments and behaviour of both groups, and in doing so I will try to answer three main questions: is the image of science given by each teaching method correct? Is it valid to emphasize scientific method rather than the subject matter of science? How can the exciting aspects of frontier science be recaptured for students with honesty?

Analysis of science

Recently, scholars who study science have clarified how scientists operate, and they have identified characteristics of scientific knowledge, but unfortunately there is little agreement among scholars, and no coherent view of science emerges. Science is a diverse and complex subject, and it has been studied in a variety of ways. The studies are rather like a series of close-up snapshots taken of the same object from different sides and angles. Each captures a particular feature of science, and some theories appear to contradict others. This creates a problem for science educators who must present a coherent image of science to their students, but do not know whose view to accept.

Representing Science

Science is hard to teach because it is hard to understand--this is one of the main themes of this thesis. Not only is the subject matter difficult, but science as an activity is also hard to understand. Sociologists of science have identified areas where misunderstandings occur. Some say that scientists "misrepresent" their activities in research papers--that they do one thing and say they do another. Others have described how attitudes of scientists toward knowledge seem to change as time goes on. Some conclude that scientists are inadvertently fooling themselves and each other, and they question the validity of scientific knowledge. I think these interpretations are incorrect, so I will give my own explanations. Reconstruction (the process of constantly reworking and reconstructing knowledge) permeates every activity of science, but has rarely been mentioned by scholars of science or scientists, and it has important implications for science education. These issues are significant because they bring out the difficulty in representing science properly. It is hard to know what is actually happening in science and to figure out how science can best be presented to students. It is difficult today to know whether to present scientific knowledge as true or tentative. In the past we presented all scientific theories as true, but recently there is a tendency to present all scientific knowledge as tentative, and to assume that students should judge all knowledge for themselves. I will describe the different positions on this issue and explain how scientists differ from others in their definitions of true and tentative.

Whose view of science should we present to students?

Our Western society values a series of qualities that seem to be associated with science, like scientific attitudes and methods. In education the methods of philosophers seem ideal. We want our children to learn how to think critically, how to consider alternative explanations, and how to make judgments. We assume that scientists judge theory using these ideal methods. For example, it is generally believed that scientists discuss theory in the same way Greek philosophers did. "It is a tradition of claims, counter claims and debates over fundamentals" (Popper quoted by Kuhn, 1977: 273). In schools, science teachers want to use these same methods to teach science. For example, constructivist teachers try to use Socratic teaching methods, and provide alternative theories and evidence so students can judge each theory for themselves. This satisfies the goals of educators perfectly, but it does not reflect what happens in science. Scientists rarely use Socratic methods, and they don't usually have a variety of theories to choose from. At any one time, not all potential theories are available and decisions must be made on the basis of incomplete evidence. If philosophical methods are rarely used in science, then it is hard to use them in science classes.

A class in the philosophy of biology, in which I recently participated as a tutor, highlighted the difference between the approach to science education of educators (or philosophers) and biologists. When evolution is taught in biology departments, the theory of natural selection is explained, the mechanisms of evolution are described, evidence for evolution is given, problems are assigned, and the implications of evolution for other aspects of biology are discussed. In the philosophy class little of this was done. Instead, students were asked to *judge* Darwin's theory of evolution. They were given a number of papers to read, some criticizing it and proposing alternatives and others defending it. On the exam they were free to take whatever position they wished, as long as they defended it with valid argument. Needless to say the professor teaching this class was a philosopher. The class contained senior philosophy and biology students; these students had already adopted many of the characteristics of members of their disciplines so their responses to the class illustrate the differences between philosophers (and educators) and scientists in their approaches to scientific topics.

In tutorial, the philosophy students argued enthusiastically about the competing theories, judging them on the quality of the arguments, but paying less attention to evidence; they were willing to make judgments with limited knowledge. Some of them calmly decided that Darwin was probably wrong. The biology students, on the other hand, did not question the theory or argue with other students; they were there to learn more about evolution. Some biology students were shocked to see the theory of evolution questioned but one admitted that this had forced her to understand the details of the theory better. Most biology students could not understand why they had been asked to read a paper in which the author clearly misunderstood the theory of evolution. Both groups of students had faults and advantages. By the standards of experts in education, the philosophy students were ideal, thinking critically, making judgments and enjoying the process. However, they did not worry about understanding the details and were not interested in asking for explanations. The biology students demonstrated what is exciting to scientists. They valued the opportunity to learn something new more than the chance to discuss, reason and assess. These students were already members of different cultures, and they illustrate the differences in approach between the cultures of education and science. Science is exciting, but not for the reasons many of us suspect.

Its fascination lies not in scientific methods, or arguing over theories; it lies in constant change, in always learning something new, and in wrestling with problems and solving them. The pragmatic way to accomplish anything in science is to accept the word of others and build on it, rather than to judge all evidence for yourself.

Scientists themselves have not played much part in the discussions about science, so their views are underrepresented. They work in a distinct culture where words like "true" and "tentative" have meanings slightly different from those commonly applied in society as a whole. Increasingly, the image of science presented to students in schools differs from the view of science held by scientists. For example, scientists are more willing than educators to accept well-supported scientific theories as true at a practical level. Similarly, scientists value scientific knowledge more than the processes of science, while experts in education value the processes and attitudes of science more than the knowledge itself. The most important change in science education over the last century has been a gradual redefinition of science by educators. The new definition is more consistent with educational theory than with science itself. The new image of scientific knowledge as tentative fits modern North American culture better than it matches the culture of science. These changes have occurred slowly, almost imperceptibly, and it is unlikely that either science educators or scientists realize how large the differences have become, or are aware of the serious implications.

SECTION 1.

HISTORY OF BIOLOGY EDUCATION

This section summarizes the history of biology over the past 130 years, the parallel history of ideas in education over the same period, and how each has affected the development of biology teaching. The analysis of biology is centred on evolution, genetics and molecular biology. It compares how these subjects were taught in universities with how they were handled in high schools. These three important fields of biology have been taught at both levels since their development, and they are related to each other. The major developments in these subjects occurred at different times: in evolution after 1858, in genetics from 1900 to 1920, and in molecular biology after 1950. This makes it possible to compare the responses of biology education to each of the advances, and to assess whether such responses have changed substantially over the past century. Since evolution and genetics have been well understood for close to a century, we can analyse how the explanations of their central concepts have changed over time. The history of ideas in science education, and their effects on science teaching, should reveal the relative impacts of biology and education on biology education. The description of biology education includes what was taught in the schools in North America, as indicated by text books, but focuses mainly on what was taught in Nova Scotia, as seen in text books, curriculum, provincial examinations and articles published in the *Journal of Education*. (All references to the *Journal of Education* will be to the journal produced by the Department of Education in Nova Scotia.)

Chapter 1

The Development of Evolution and Genetics before 1950 and its Impact on Biology Education

Both biology and biology education changed in the late nineteenth century. Public education began in Nova Scotia in 1866, so many more children attended school, and greater attention was paid to curriculum and teaching methods. There were equally large changes in biology. Darwin's theory of evolution, proposed in 1858, altered nineteenth century research and teaching, and had a far reaching influence on society.

Evolution

In *The Origin of Species*, published in 1859, Charles Darwin put forward two hypotheses: that evolution occurs and that the specific mechanism for evolution is natural selection. The idea that evolution occurs (that new species arise from old and that organisms have descended from common ancestors) was accepted readily. Others, especially Lamarck had proposed it earlier, but it was Darwin who gathered enough evidence to convince the scientific community. The idea of common descent explained why different species have similar structures and it immediately revolutionized both research and teaching in biology. Scientists used fossils, comparative anatomy and embryology to look for common patterns between species, and to establish family trees. In contrast, the theory of natural selection as a mechanism for evolution was not well understood, and was not fully accepted until the period (1936-1947) called the evolutionary synthesis (Mayr, 1982).

Darwin included a number of related ideas in his theory of natural selection. Even though most populations have a great capacity for increase, they actually stay about the same size from generation to generation. Since more individuals are born than can survive and reproduce, there must be a struggle for existence among the individuals of a population. The individuals most likely to survive and reproduce are those that are best adapted to the environment in some way(s). Organisms inherit traits from their parents, and since the parents differ from each other, so do the offspring; this provides a heritable source of variation within the population. The best adapted individuals will leave more descendants, and these descendants will inherit the parents' traits that favor this adaptation. This differential survival and reproduction is natural selection. Over the generations the process of natural selection, together with variability of environments in space and time, will lead to a continuing gradual change in populations, and to the production of new species.

The idea that evolution is a gradual process was accepted by very few people during the nineteenth century. The dominant philosophy of the nineteenth century supported the idea that a new type might arise suddenly and eliminate those that were inferior, but it was not compatible with the concept of gradual improvement (Mayr, 1982). Similarly, the idea that evolution is a phenomenon of populations rather than individuals was not accepted for a long time. Darwin saw that individuals within species were unique, but most naturalists used to thinking in terms of variation between species but not variation within populations. Even today it is hard to think of natural selection as a statistical concept. Having a superior genotype does not guarantee survival and abundant reproduction; it provides only a higher probability. In the nineteenth century, evolution was most commonly imagined as a process in which one species suddenly appears and another is eliminated. It was hard to think of a highly variable population in which new variations are produced continuously, some of them superior and some of them inferior to the existing average (Mayr, 1982).

Early History of Genetics

In the late nineteenth century everybody knew that evolution could not be properly understood until the mechanism of heredity was known. Darwin stated that natural selection acted on small, continuous, inherited variation between individuals. He proposed a blending theory of inheritance called pangenesis, in which the "seeds" or representatives of the various parts of the body accumulated in the gonads. However, this was not well accepted, and a number of other theories were proposed. The controversies about heredity centred on two basic issues: whether genetic variation was continuous or discontinuous, and whether acquired characteristics could be inherited.

Continuous and discontinuous variation

Two parallel approaches to genetics were taken in the nineteenth and early twentieth century: one by hybridists (e.g., DeVries and Bateson), and the other by biometricians (e.g., Galton). Both groups believed that there were two kinds of variation, continuous and discontinuous, but they disagreed about which kind of variation was inherited, and thus involved in evolution (Allen, 1975; Mayr, 1982). Discontinuous variation occurs in recognizable discrete traits that apparently have no gradations between them. Eye colour is discontinuous because people have blue or brown eyes (with admitted variation within these categories). Continuous variation occurs in a graded series, running from one extreme to the other. Human height is continuous because people are not only short, medium and tall, but also every gradation between.

Hybridists and discontinuous variation. Hybridists thought that natural selection must act on large-scale variations of the discontinuous sort rather than on small, continuous variations, as proposed by Darwin. They argued that continuous variation was caused by environmental effects, so it was not inherited, and not involved in evolution (Allen, 1975). DeVries introduced the word "mutation" for any drastic change in form that was great enough to produce a new species, and in 1901 he proposed that individuals can undergo mutations by genetic changes large enough to produce a new species within one generation. He used the sudden development of a new species of evening primrose as evidence for this theory of sudden evolution. Natural selection might still occur, but it would act on mutations, so evolution would not be a gradual process as Darwin had proposed, and the real force behind evolution would be mutation rather than natural selection. The mutation theory of evolution was popular until 1910 when it became clear that the evening primrose provided almost the only example supporting it.

Biometricians and continuous variation. Biometricians believed that continuous variation was inherited; discontinuous traits are really special cases of continuous variation. They studied variation at the level of populations, measuring visible quantitative traits like height and weight, and analysing them statistically. Galton proposed the Law of Filial Regression. He argued that characteristics are preserved over many generations. Even though children are not entirely like their parents, each individual inherits a portion of his or her characteristics from each grandparent. Therefore heredity must be due to many independent bearers or particles (blending inheritance). New variations in a population, no matter how pronounced at first, would be weakened in effect by each generation of crossbreeding. As a result, offspring on average tend to be pulled back toward the mean; exceptional parents have less exceptional offspring. Galton concluded that a population would not evolve unless a change in the environment pushed it toward a new mean (Mayr, 1982). Therefore, Darwin's theory that evolution occurs by a gradual adaptation to the environment could not be correct; evolution would only be possible in changing environments.

The dispute over continuous and discontinuous variation was resolved by T.H. Morgan and his students between 1910 and 1915. They found that continuous and discontinuous variation are really part of the same phenomenon, and both are inherited. The misunderstanding about variation occurred because scientists failed, until 1909, to understand the difference between genotype (the alleles that an individual has for a trait) and phenotype (the expression of the genes in the individual). Some phenotypic traits like eye colour are largely or entirely determined by one gene. If an individual has two alleles for blue eye colour, his eyes will be blue, while if at least one of his alleles designates brown eye colour, his eyes will be brown. The phenotype (the effect we see) appears to be discontinuous because there are just two possibilities. On the other hand, phenotypic traits like human height are determined by more than one gene. If the trait is controlled by several genes, there will be many possible combinations in the population and the result will appear to be continuous. If height, for example, is determined by four or five genes, and an individual has two alleles for each gene, then there are many possible combinations of alleles, all affecting the same trait. An individual with short alleles for each of five genes will appear to be very short; another individual with short alleles for four of the genes but tall alleles for one gene will be marginally taller than the first, and so on. In addition to the genetic component, every phenotypic trait is also influenced by environment. Individuals who have alleles that should make them tall, will not be tall if they are deprived of food while they are growing. This looks simple now, but it was much confused at the turn of the century.

Soft and hard inheritance

Soft inheritance. There were two separate theories involving the inheritance of acquired characteristics. The first was proposed by Lamarck who said that characteristics acquired by use and disuse can be inherited. In the commonly used example of this mechanism, giraffes lengthen their necks in an effort to reach high branches on trees. In inheriting the lengthened necks, their offspring are inheriting characteristics acquired during their parents' lifetimes. Although many nineteenth century scientists did not accept Lamarck's theory, they did accept the second, less extreme theory of "soft inheritance." The term "soft" referred to the belief that the genetic material is pliable or changeable. Soft inheritance implied that genetic material could be directly modified by climate, other environmental conditions, or nutrition.

Hard inheritance. The cell biologist August Weismann (1834-1914) supported hard inheritance, the idea that genetic material is not changed by the environment. His "continuity of the germ plasm" theory, postulated in 1885, explained why soft inheritance is impossible (Mayr, 1982: 698). Offspring inherit from their parents a substance (with a definite chemical constitution), that is located on chromosomes within the nucleus (Wilson, 1900). There is no mechanism allowing the inheritance of acquired characters because the inherited substance is located in the nucleus of the "germ track" (gonad), which has no communication with the rest of the body.

Because the theory of natural selection is so well accepted today, we find it hard to realize that there was little reason to accept it in the nineteenth century. A surprisingly large number of scientists accepted soft inheritance until after 1910, when Morgan's work demonstrated that genes represent hard inheritance. As long as the nature of genetic material was unknown, soft inheritance seemed to explain adaptation better than the natural selection because it seemed more logical that genetic material should be altered by the environment than that genetic variation should be random. Even Darwin occasionally seemed to accept soft inheritance (Spencer, 1898).

The impact of Darwin's theory of evolution on biological research

Darwin's work had an enormous impact on biology. It influenced not only what was studied for the next forty years, but also how it was studied. Once the basic concept of evolution was accepted, it became possible to trace out family histories of different species, and morphology (including embryology, comparative anatomy, paleontology and cytology) dominated biological research. Many nineteenth century scientists copied Darwin's approach of creating a large general theory made up of a number of parts, and of supporting this theory with evidence from a variety of fields. Comprehensive theories that attempted to explain seemingly unrelated questions were typical of biology after 1859 (Allen, 1975).

Mendelian genetics

Mendel published his work in 1866, but nobody (including Mendel) realized how important it was until 1900. It is now generally agreed that in 1866 Mendel did not mean exactly what was later attributed to him; he did not have the clear cut concept of a gene, with alleles that segregate during meiosis, that biologists now read into his work (Allen, 1975; Mayr, 1982; Olby, 1990b). However, even if his ideas were fuzzy enough to disturb some historians of science, they were still remarkable enough to impress modern biologists (Mayr, 1982). Mendel drew three important conclusions:

1. Dominant and recessive factors (which we now know as alleles of a gene) are independent of each other in a heterozygote. When a heterozygote produces offspring, the independent factors separate without affecting each other. (Mendel was rather confused about what happened in a homozygote.)

2. When gametes are formed, only one of the characters of a factor (Mendel called it *Anlage*) goes to each gamete. This is true in both heterozygotes and homozygotes, and

it explains the phenomena of segregation and recombination.

3. During fertilization, the particular combination of factors is a matter of chance. In large samples, the offspring show the dominant: recessive trait in a 3:1 ratio (Olby, 1979; Mayr, 1982).

The rediscovery of these conclusions, and the rediscovery of Mendel's paper in 1900, had an immediate impact on research in biology. Plant and animal breeders reinterpreted their work in Mendelian terms because this theory was consistent with their experience, and they were able to use it as a tool to improve breeds. Evolutionary biologists used Mendel's work to support their arguments. William Bateson claimed Mendelian genetics as evidence of discontinuous variation, making more scientists aware of it, but at the same time raising opposition to it by putting it on one side of a controversy. Mendelian theory also showed how an experimental approach could be used in biology. In the nineteenth century most research was descriptive and speculative, with large comprehensive theories (like the theory of natural selection) that integrated evidence from a variety of sources and disciplines, but could not be easily tested (Allen, 1975: 9). At the beginning of the twentieth century there was a revolt against this style in favour of the experimental approach. The rediscovery of Mendel's work began a period in which biologists developed smaller, testable theories; they replaced observation with experimental techniques, and studied function rather than structure.

However, Mendelian theory was only gradually accepted between 1900 and 1910 because there were a number of problems associated with it: there was confusion about what Mendel's "factors" (alleles of genes) represented (before genotype and phenotype were differentiated); there were relatively few examples in which Mendelian laws could be demonstrated; traits did not always appear as dominant and recessive; and there was no physical proof of Mendel's genes. Thomas Hunt Morgan distrusted Mendelian genetics in 1909, even though he later confirmed and extended Mendel's work with experiments on *Drosophila*.

Relating genes to chromosomes.

In 1902 Sutton suggested that genes were probably located on chromosomes because chromosomes and genes behave the same during meiosis (Allen, 1975: 56). By 1905 Wilson and Stevens showed that sex was related to an extra pair of chromosomes, and that the chromosomes in this pair were not identical in one of the sexes. By 1912 there was cytological evidence relating genes to chromosomes, and T.H. Morgan accumulated further evidence after that (Mayr, 1982).

The Morgan school of genetics

In 1908 T.H. Morgan began to breed *Drosophila* to test whether large scale mutations of the sort proposed by DeVries could be found. He tried to induce mutations by exposing flies to x-rays, chemicals and different temperatures. Only small changes occurred, and he called these mutations. He found a white-eyed male and mated it with a normal red-eyed female, then mated their offspring. This demonstrated that the white-eyed condition occurs only in males, and by 1910 he had related the white eye colour in *Drosophila* to inheritance of the Y chromosome. His results could all be explained with

Mendelian theory.

Over the next five years Morgan and his students made enormous progress. They proposed that crossing over occurs between chromosomes during meiosis, and this concept allowed them to map chromosomes and show that specific genes are located in a linear fashion on particular chromosomes. They published a book called *The Mechanisms of Mendelian Heredity* (Morgan, Sturtevant and Bridges, 1915) that completely supported, and added to, Mendelian genetics. It was immediately well accepted, and genetics was fairly well understood by 1920 (Mayr, 1982).

Theories of Evolution, 1900-1950

Between 1895 and 1936, research on evolution was dominated by controversy. Until 1910, experimental geneticists and naturalists had opposite beliefs about evolution, and little communication with each other (Mayr, 1982: 566). They did not agree on whether evolution was gradual or sudden, inheritance was soft or hard, and whether genetic change was due to mutation pressure or selection pressure (Mayr, 1982). Geneticists believed that genetic variation was discontinuous, and large-scale mutation was the major force behind evolution. Naturalists believed that continuous variation was important for evolution, accepted soft inheritance, and supported Darwin's theory of natural selection as the major cause of evolution. The two groups dealt with biology at different levels; the geneticists dealt with genes and individuals, while the naturalists dealt with populations and species (Mayr, 1982). By 1910 phenotype and genotype had been distinguished, so disputes over discontinuous and continuous variation, and soft and hard inheritance, ended.

Confirmation of natural selection. Population genetics (the study of changes in gene frequencies in populations) began with the introduction of the Hardy-Weinberg equilibrium principle in 1908. By 1930, population geneticists had confirmed that large amounts of genetic variation exist within populations, and that natural selection is important. This established the basis for gradual Darwinian evolution, and confirmed that soft inheritance was not necessary for natural selection.

Role of geographical isolation in forming new species. By 1942 naturalists, like Ernst Mayr, described what causes reproductive isolation between populations, and stressed the importance of geographic isolation on the formation of new species. Both population geneticists and naturalists contributed to the evolutionary synthesis between 1936 and 1947. They accepted that most evolution is gradual, but occasional polyploidy (chromosome doubling) can lead to the sudden production of a new species because individuals are no longer able to interbreed. (This was what had occured in the evening primrose.) They also recognized that different populations can undergo different rates of evolution, and that evolutionary changes occur fastest in small isolated populations.

Impact of society on biological research

Allen (1975) has argued that scientific research is influenced, at least indirectly, by predominant ideas and attitudes in society. We can see this by comparing research achievements with the social climate during different periods. Between 1900 and 1920, both society and science were mechanistic. Capitalism and industrialization tended to reduce individuals to the status of machines. Social Darwinism was used to justify good conditions of life for industrialists and poor conditions of life for workers. Political leaders drew boundaries around geographic regions, ignoring the cultural and ethnic distribution of populations (Allen, 1975: 108). The mechanistic approach was also clear in biology. There was an assumption that biology could be reduced to the fundamental laws of physics and chemistry. Research became more experimental, and was based on smaller theories that could be tested by experiment. In physiology, components of animal bodies were isolated and subjected to specific treatments, and in genetics individual traits were identified and related to specific chromosomes. It seemed unreasonable even to speculate on features that could not be tested.

After 1920 there was a change from a mechanistic to a holistic approach, both in society and in biology. The holistic approach viewed society as a living, integrated structure in which balance was required. In politics, the static relationships that had existed between the major powers were replaced by a dynamic equilibrium of shifting, constantly changing, spheres of influence, and the older, *laissez-faire* capitalism was replaced by Keynesian economics, by which governments tried to regulate economies and maintain an equilibrium (Allen, 1975: 109). In biology too, the goal was to explain the whole organism rather than just to isolate and study its parts. Systems that maintain homeostasis, like nervous and hormonal systems, were studied. The holistic approach was also visible in the integration of different fields of knowledge in biology. The evolutionary synthesis from 1936 to 1945 integrated knowledge in genetics, evolution and natural history. Similarly, after 1940 there was a synthesis of knowledge from a variety of fields to form molecular biology.

Teaching Genetics and Evolution

From the beginning, evolution was taught in all biology courses and few textbooks questioned its validity. Evolution was not just another topic to study; it provided an underlying explanation for similarities and differences between organisms, and a new basis for classification. Even when the word "evolution" was not mentioned, evolution was still being taught. Therefore, differences in particular explanations for the processes of evolution were minor compared to the enormous impact evolution had on all other aspects of biology education. In the nineteenth and early twentieth century, biologists controlled what was taught in the schools. They wrote the textbooks and prepared the examinations, so science teaching closely mirrored scientific research. Scientists compared organisms with each other as they gathered evidence for evolution; similarly, students compared organisms with each other as they learned biology. What may seem to us now to be boring surveys of the phyla and bad science education were, in the late nineteenth century, state-of-the-art science and exciting evidence for a great theory.

In the late nineteenth century it was common to teach biology as a survey of organisms from simple to complex, imitating the course of evolution. This approach was popular in university texts like *A Manual of Zoology* by T.J Parker and W.A. Haswell published in 1900, and *Animal Life* by D.S. Jordan and V.L. Kellogg published in 1900. Thomas Huxley, introduced an approach, he called the "type" approach, to make biology more interesting and easier to learn. Rather than beginning with the simplest organisms then working to the most complex, he began with the most familiar groups of organisms and worked to the less familiar. He chose a familiar organism like a rabbit or fish, treated it as a representative type of its phylum or class, and taught about it in detail, morphology first, then embryology, ecology and physiology. Other members of the group were assumed to have the same basic structure. Once students were familiar with one organism, he would move on to other related groups, comparing the new group to the one already learned. The "type" approach made the study of organisms easier because it always began with the most familiar organisms, but at the same time, it emphasized the common history of organisms and common body plan produced by evolution, yielding the same conclusions as the survey approach. Thomas Huxley commented:

> "Consider now, where our inquiries have led us. We studied our type morphologically, when we determined its anatomy and its development, and when comparing it, in these respects, with other animals, we made out its place in a system of classification. If we were to examine every animal in a similar manner, we should establish a complete body of zoological morphology" (Huxley, 1867: 130).

This approach is still an effective method of teaching this aspect of biology. In the nineteenth century morphology was stressed in both teaching approaches, but after 1900 physiology was increasingly emphasized.

Teaching genetics and evolution in Nova Scotian schools

By 1893 the curriculum and text books used in Nova Scotian high schools were well defined. Botany was taught in grade 9, agriculture in grade 10, physiology in grade 11, and a choice from a number of sciences, including botany and zoology, in grade 12 (see Appendix 1). Agriculture and physiology (health) contained some biology but were oriented toward practical goals. The biology texts used in Nova Scotia from 1893 to 1940 were written by university professors, and were among the most popular texts of their time (Downing, 1925). Thus Nova Scotian students were learning the same general concepts learned throughout North America.

Only one of the textbooks used in Nova Scotia opposed evolution; this was *Handbook of Zoology*, written by J.W. Dawson in 1870, and used as a textbook until 1899. Dawson describes only the superficial external features of organisms used in the Linnaean system of classification. His anti-evolution stance was compatible with his belief in creation:

> "In like manner, it is obvious that we must assume a separate origin for each species, and that we need not assume more than one origin. Practically, species remain unchanged, and do not originate from one another" (Dawson, 1870: 25).

A second zoology text (used in grade 12 from 1893 to 1899), *Zoology, Descriptive and Practical* by B. P. Colton, does not mention evolution by name, but adopts Huxley's type approach. The botany text, *The Essentials of Botany*, by C.E. Bessey (used in grade 12 from 1893 to 1909), also uses the type approach and describes the evolution of plants, but does not explain the theory of natural selection.

The first text to explain the theory of evolution was *An Introduction to Zoology*, written in 1889 by Ramsey Wright (a professor at the University of Toronto) and used in Nova Scotia from 1900 to 1910. Wright used the type approach, beginning with the catfish as a type form of vertebrates generally, then the chicken and cat as representatives of birds and mammals respectively, and the crayfish, spider and grasshopper as examples of arthropods. He does not present the same picture of evolution that we accept today because he seems to accept soft inheritance:

> "The theory stated in the preceding paragraphs is that of the Origin of Species, associated with the names of Wallace and Darwin; it will be observed that while resting upon the large amount of variation offered, it does not attempt to explain the cause of such variation. This is attributed by certain American zoologists, --of whom Cope is the chief representative--to the direct action of the environment, for example the gradual preponderance assumed by the central digits in the Ungulates would be explained by the greater strain received by those reaching the ground. Strict Darwinists do not consider such an explanation to be sufficient, because there are many instances of protective resemblance and mimicry where just as remarkable modifications of form are to be met with, which could not be attributed to such a direct action of the environment. On the other hand, we have met in the preceding chapters with so many instances of the adaptation of the organism to its habitats that it seems difficult to believe that such remarkable correspondence should only be the result of selection from variations tending to occur in every direction" (Wright, 1889: 295).

The text, *Principles of Botany*, written in 1906 by J.Y. Bergen and B.M. Davis (used in grade 12 botany from 1910 to 1939), explains the theory of evolution and presents plants in order of their evolutionary history. Bergen and Davis explain Darwin's theory of natural selection, using excellent examples to illustrate each point, but they are inclined to accept soft inheritance and they mention DeVries' theory of mutation:

> "Botanists at present are considerably divided on the question of the origin of species, some believing that they are mainly derived from the perpetuation and intensification of slight variations, while mutations are so infrequent as not to signify much in this connection; others, again, believe that mutations are the source of species, and that variations can only give rise to varieties. There seems to be no good reason for doubting that both variation and mutation have been and are efficient in the production of new species" (Bergen and Davis, 1906: 498-499).

Although they do not mention Mendelian genetics, Bergen and Davis do describe the recent improvements of agricultural crops, like apple, beans, corn and wheat, in detail. Their account of work done in Minnesota on the development of new varieties of wheat allows the reader to visualize the whole process. They explain how to remove the pollen from the male parts of flowers and brush it on to the stigma, how to collect all the seeds and plant them, and how to choose the best ones to use as the parents for future plants. This book was completely up-to-date in 1906, but it was retained as the text until 1939, and I could find no indication that newer editions of the book were used.

Beginners' Botany (used as the grade 9 text from 1918 to 1932) was written in 1908 by L.H. Bailey, a geneticist. He describes the theory of natural selection clearly, at just the right level for grade 9 students. It is easy to see why these excellent texts were used throughout North America. The following passage explains selective breeding:

> "So all our common and long-cultivated plants have varied from their ancestors. Even in some plants that have been in cultivation less than a century the change is marked: compare the common black-cap raspberry with its common wild ancestor, or the cultivated black-berry with the wild form. By choosing seeds from a plant that pleases him, the breeder may be able, under given conditions, to produce numbers of plants with more or less of the desired qualities; from the best of these, he may again choose; and so on until the race becomes greatly improved. This process of continuously choosing the most suitable plants is known as selection. A somewhat similar process proceeds in wild nature, and it is then known as natural selection" (Bailey, 1908: 7-8).

Was Evolution taught in North American schools?

The impression is sometimes given that evolution was rarely taught in North American schools before 1960 (Skoog, 1979; Rosenthal and Bybee, 1987). Bentley Glass said:

> "The great theme of organic evolution, which is central to the organization and interpretation of biology, and which has become vastly developed in the past forty

> years beyond simple Darwinian schema, was disregarded and most often remained unmentioned. The fear that a book with the horrid word "evolution" in it could not be sold to school districts in large parts of the United States was quite sufficient to suppress it. Sometimes one found a euphemistic reference to the 'theory of organic development;' more often evolution was simply excluded" (Glass, 1970: 24 and 25).

Comments like this are not substantiated by most textbooks. Only Dawson (1870) denied the existence of evolution, and the authors of most other books either discussed the theory of evolution or described how specific plants and animals evolved. Questions about evolution were asked on the provincial examinations for grade 12 students. Students were asked about the evolutionary relationships between groups of plants. For example, the following questions were asked on Provincial examinations:

> "Discuss the evolution of the flower, under some such headings as the differentiation of the perianth, arrangement of sporophylls and fusion of parts" (*Journal of Education, 1910:* 37).
>
> "State what seems to you to be a reasonable theory to account for the great multiplicity of different kinds of plants on the earth at the present time" (*Journal of Education, 1930 (Oct):* 42).

All textbook writers were teaching evolution, even when they did not mention the theory of natural selection. Even writers of textbooks for religious schools could not avoid considering the evolutionary relationships among organisms, so they were teaching evolution implicitly while they avoided it explicitly.

Chapter 2

The Influence of Molecular Biology on Biology Education after 1950

Molecular Biology

Molecular biology (the study of large polymeric molecules in cells), began as a branch of biochemistry (the study of the chemical reactions in which these and other molecules participate). But molecular biology eventually drew knowledge from a variety of fields: molecular geneticists tied genes to the specificity of enzymes; chemists worked on the structure and function of molecules, especially proteins; X-ray crystallographers worked on the three-dimensional structure of large molecules; and microbiologists determined that DNA was the genetic material. Their work suddenly came together when Watson and Crick deduced the structure of DNA, so after 1953 there was a clear path of research called molecular biology.

Biochemistry. In 1897 Buchner discovered the enzyme zymase in an extract of yeast cells, and showed that it could break down sugar in a cell-free system (Allen, 1975: 157). By 1900 enzymes had been isolated and their basic catalytic activity identified. Scientists thought that enzymes were proteins and knew that proteins were relatively large molecules, but they did not know the precise chemical structure of proteins, or even whether they were simply aggregates of smaller molecules (Allen, 1975: 164). Two schools of biochemists developed, one focused on the chemical activities of proteins, and between 1930 and 1960 this group had identified the steps in many metabolic pathways. The other school identified the structure of proteins, and by 1935 they knew that proteins had a specific chemical structure and a definite atomic composition.

Biochemistry and molecular biology depended more than most fields, on the development of new equipment and techniques. For example, the ultracentrifuge, which was developed in 1925, allowed biochemists to separate large molecules of different sizes. Similarly, a method of crystallizing proteins, developed in 1926, helped purify these molecules for analysis, and methods for synthesizing peptides were developed in 1932. Chromatography was discovered in 1906, and by the mid-1940s it was used to work out the sequence of amino acids in a protein.

The link between genes and enzymes. After the existence of genes was firmly established, scientists began to ask how genes could control specific characters, and some suggested that genes might control cellular metabolism. In 1908 Archibald Garrod indirectly demonstrated that genes affect steps in specific biochemical pathways, but neither theory nor techniques were sufficiently well advanced to study this question further. T.H. Morgan and his students showed that genes are located on chromosomes, but did not attempt to study their molecular nature or biochemical function. The link between genes and enzymes was finally made in the 1940s, when Beadle and Tatum showed that genetic mutations produce blocks in metabolic pathways, and concluded that a gene must direct the synthesis of an enzyme (Olby, 1974).

The structure of molecules. Linus Pauling proposed a general theory of chemical bonding in 1931, showing that a variety of chemical bonds act between atoms in proteins. He developed the concept of weak interactions and proposed that a protein (made up of a chain of amino acids) is not a long, string-like molecule, but has a three dimensional structure because it folds back on itself in a variety of ways (Allen, 1975: 171). In the 1940s, Frederick Sanger worked out the sequence of amino acids in insulin. Then in 1957 and 1959 John Kendrew and Max Perutz solved the three-dimensional structures of myoglobin and hemoglobin using X-ray crystallography. This allowed them to explain how these proteins function. Although they completed this work after the structure of DNA had been solved, the principles embodied in their work had considerable influence on Watson and Crick's efforts to built a model of the DNA structure (Judson, 1979: 561).

DNA--the genetic material. Throughout the 1930s scientists thought that proteins must be the source of genetic information. Proteins were known to consist of a linear sequence of specific units, and were thought to be the only molecules complex enough to carry sufficient genetic information. However, Frederick Griffith in 1928 showed that if a living benign strain of a bacterium is injected into an animal host simultaneously with a nonliving (usually heat-killed strain) virulent strain, some of the benign forms became actively virulent. This result surprised everybody, and Oswald Avery and his colleagues spent years isolating the material that caused the change. They expected the transforming substance would be protein, but it proved to be DNA. Since DNA was able to convert one genetic type of bacterium into another, they hesitantly proposed in 1944 that DNA is the genetic material. Nobody did much about Avery's conclusion at that time because they did not know what to make of it (Judson, 1979: 63).

A group led by Max Delbruck, and informally called the phage group, began in the early 1950s to use bacteriophage (a virus that infects bacteria) to study genetic material. In 1952 Alfred Hersey and Martha Chase labelled the DNA of phage with radioactive phosphorus, and the protein coat with radioactive sulphur to follow the molecular events during phage infection. They showed that when a phage infects a bacterial cell, it injects its DNA into the host, leaving the protein coat on the outside (Raven and Johnson, 1989).

The model of DNA. Even though it was becoming obvious before 1953 that DNA must be the genetic material, nobody had a good concept of it. But when Watson and Crick proposed a molecular model for DNA in 1953, the picture cleared immediately. Finding the structure of DNA allowed the various kinds of evidence to be explained all at once, and it opened up a variety of possibilities for future research. By 1957 molecular biologists understood how DNA replicates, but they had more difficulty finding out how the message in DNA is translated into the sequence of amino acids in protein. They found ribosomal RNA and transfer RNA, but could not, at first, see how the genetic code was carried to the ribosome. The existence of messenger RNA was postulated in 1960, but messenger RNA itself was not found until 1961. The genetic code was known by 1966 (Judson, 1979: 488). By 1970 the composition of genes was understood (at least in outline), as well as how genes replicate, how they are translated into a sequence of amino acids in proteins, how gene expression is controlled, and how proteins function and interact.

The changing view of cell structure and metabolism

There was a dramatic change between 1940 and 1960 in the way scientists understood organisms at the cell and molecular level. In the 1940s biochemists identified the steps in metabolic pathways (such as cell respiration and photosynthesis), and identified the amino acid sequences of proteins. The electron microscope was developed in the late 1940s, and by the early 1950s, cell biologists could see cell structures in detail and understood them in new ways. Molecular biology developed rapidly after 1953; not only did scientists understand DNA, but they could also visualize enzyme activity at a totally new level by 1959, when the three-dimensional structures of proteins were worked out. Integration of this knowledge led to a new approach to biology. Scientists no longer explained phenomena just at the level of individual organisms, but also at the level of cells and molecules. The differences between organisms that were so obvious at the level of individual organisms were overshadowed by their similarities at the cellular level. Since many of the molecules and cell structures studied were basic to life, they were present in all living organisms. Therefore scientists began to study the universal principles and properties of life rather than the differences created by evolution. Jacques Monod, described the universality of living processes when he said "What is true for *E. coli* is also true for elephants" (Judson, 1979: 613).

Repeating patterns. Joseph Schwab, an educator who helped reform the biology curriculum in 1960, argued that biology had changed in a qualitative way in the mid-twentieth century. He said that early in the century scientists just "catalogued organisms" and "collected facts," replacing them with newer more modern facts as they became available.

"Science has changed. Sixty years ago science was a matter only of seeking the

> facts of nature and reporting what one saw. Scientific knowledge and permanent knowledge were seen as synonymous. Science was supposed to grow by accretion, new facts were added to old ones. Older ones were rendered more precise, but on the whole science was a collection of unrelated statements so a new one could not send an old one to extinction" (Schwab, 1969: 181).

In contrast, he believed that after 1950 biologists looked for patterns that would allow them to explain phenomena, so "all facts were looked at in the light of other knowledge." For Schwab this explains why biology was better after 1950 than before (Schwab, 1962: 201). However, the evidence does not support this claim. Biology was quantitatively different after 1950; different tools were used to study organisms and different kinds of knowledge were learned, but biology was not qualitatively different.

The era of molecular biology from 1950 to 1960 was not any more exciting or challenging than the period from 1860 to 1870, when scientists realized the implications of evolution and began to look for evidence of the relationships between organisms. Similarly, the growth of genetics from 1900 to 1920 was just as fast-paced and productive as the development of molecular biology from 1950 to 1970. Edmund Wilson (1900) demonstrates in his book, *The Cell in Development and Inheritance* that biology was just as important and challenging in 1900 as now. Schwab suggests that only after 1950 did biology become a "search for patterns and explanations" (Schwab, 1962: 201), but Darwin's theory of evolution and Mendel's laws of inheritance were precisely that. In the nineteenth century the "catalogues of organisms" that Schwab refers to were exciting evidence for "patterns" in evolution.

Rapid change but not overthrow. Biology has not gone through a series of revolutions in which older paradigms have been replaced with new ones. No set of well accepted ideas has been overthrown. Instead, there has been an opening-up of knowledge, as equipment and techniques have allowed scientists to study organisms in new ways. The new techniques allow us to see organisms differently, but they have not led to an overturning of older knowledge. Now we can understand organisms at the molecular level rather than just at the levels of organs or tissues, but the understanding at the level of the organism is still valid. The term revolution can be used in biology only to mean rapid change, not overthrow. There have been three periods since 1850 when subjects were opened-up quickly and understood better. The first began with Darwin's theory of evolution in 1958; it changed both research and teaching in biology. Scientists looked for evidence of evolutionary relationships and began to form large encompassing theories that would explain evolution, development and cell structure all at once. The second major change came after 1900, as scientists developed genetics, but also began to form smaller testable theories, and used experiment rather than observation. In the classroom, more importance was placed on function than structure, and increasingly courses centred on an explanation of organ functions, like digestion or respiration, rather than a comparative survey of organisms. The third change came after 1950 with the opening up of biochemistry, the development of the electron microscope and the discovery of the structure of DNA. Life was suddenly understood at the molecular level. In classrooms, the functions common to all organisms were taught at the molecular, cellular or population level. Perhaps there will soon be a fourth revolution. Now that DNA can be manipulated and sequenced, there will be a sudden development of new knowledge, as biological systems can be simulated and replicated. The years, 1858, 1900 and 1953 have much in common; they were turning points in the way biologists viewed life. All three were followed by periods of about 40 years with no major change, and on all three occasions, educators thought their experiences were unique, but as we look back, we can see they were not.

The Impact of Molecular Biology on Biology Education

Until 1950, biology was mainly taught at the level of the individual organism (comparative physiology and a survey of organisms), but after 1950, the emphasis moved from individual organisms to cells and molecules. At the same time ecology expanded into a serious science, and animal behavior was added to biology textbooks. New courses were based on cellular, molecular and population levels of organization. Instead of observing differences between organisms and focusing on evolution, the similarities were noted and universal processes, like cell respiration and protein synthesis, were studied.

Introduction of the molecular approach into college textbooks. As many strands in the molecular approach to biology joined suddenly, college textbooks also changed quickly. Textbooks written before 1950, even if completely up-to date, barely mentioned biochemistry or molecular biology. Although much of the definitive research in those areas was carried out in the 1940s, it did not appear slowly, as each discovery was made, but fairly suddenly, after the implications became clear to all scientists. The new approach became evident in 1950 and can be found in the textbook, *General Biology* written by Gairdner Moment (1950). This text includes an introduction to chemistry and biochemistry, using the same general approach found today. Moment describes photosynthesis in some detail; he gives the formula for chlorophyll and compares it to hemoglobin, describes experiments done by biochemists, and summarizes the different reactions of photosynthesis (Moment, 1950: 100). His book contains one of the first chapters on ecology to include curves and equations for population growth, and it has a chapter on behavior. The organization of the text is significantly different from earlier texts. Moment comments on the dramatic changes in biology and the new levels of organization in biology.

> "By providing a unifying principle, the concept of levels of organization is doing for twentieth-century biology what the theory of evolution did for the biology of the nineteenth century" (Moment, 1950: 22).

Mary Gardiner (1952), in *The Principles of General Biology*, takes this new approach further. She includes chemistry, biochemistry and ecology, but what she leaves out is more noteworthy than what she includes. She omits most descriptions of the diversity of organisms and concentrates only on what organisms have in common. The change in approach was fairly complete by the time Claude Villee wrote *Biology,* Third Edition in 1957. This text has the modern format. It contains: molecular components of cells and cell structures (including details from electron micrographs), biochemistry (including explanations about enzymes and metabolism), plants (discussing universal functions like the carbon cycle and photosynthesis rather than morphology), organ systems in animals, genetics, evolution, molecular biology, and ecology. Even though molecular biology and biochemistry appeared suddenly, they were still a very small portion of the texts because relatively little was known about them. However the organization of the texts changed, and these subjects were given priority, so they had a greater impact than would be predicted by quantity.

How explanations change over time

I will describe how genetics and molecular biology are presented in introductory university textbooks when these subjects are new, and also when they have been understood for some time. This will provide a comparison of how an area of science is taught when its major concepts are well understood (as they were for genetics since 1930, and molecular biology since 1985) with how they are described when the area is still in a state of change (as genetics was in 1916, and molecular biology was in 1957 1968). The introductory college textbooks used for this comparison are shown in Table 1 below.

Since the early and later editions of each of these texts (except those of Gager and Barrows) were produced by the same publishers and authors, we can expect these editions to be similar in approach, and the differences are more likely to be caused by genuine changes associated with time rather than differences in personal approach.

Table 1. Textbooks used to compare the treatment of genetics and molecular biology by authors over time

Year	Author	Title
Genetics		
1916	Gager, C.S.	*Fundamentals of Botany*
1930	Barrows, H.R.	*College Biology*
1967	Keeton, W.T.	*Biological Science First edition*
1993	Keeton, W.T., and Gould, J.L.	*Biological Science Fifth edition*
Molecular biology		
1957	Villee, C.A.	*Biology Third edition*
1985	Villee, C.A., Solomon, E.P. and P. W. David	*Biology*
1967	Keeton, W.T.	*Biological Science First edition*
1993	Keeton, W.T., and Gould, J.L.	*Biological Science Fifth edition*
1968	Curtis, H.	*Biology First edition*
1989	Curtis, H. and Barnes, N.S.	*Biology First edition*
1973	Orians, G.	*The Study of Life Second edition*
1995	Purves, W.K., Orians, G, and Heller, H.C.	*The Study of Life Fourth edition*

Genetics in university textbooks

Genetics in 1916. In 1916 genetics was developing rapidly, and the description given by C.S. Gager in his text, *Fundamentals of Biology*, is closer to genetics as it was in 1905-1910. He describes the work of Mendel in detail, is enthusiastic about DeVries' theory of mutation (generally discredited by 1910), and describes Galton and the biometricians (who also had lost favour by 1910). He does not mention the work of T.H. Morgan (begun in 1908) or the chromosome theory of inheritance (first proposed in 1902), but he does emphasize the difference between genotype and phenotype (proposed in 1909). Gager presents genetics as if he were writing a review paper. He is enthusiastic about the new experimental approach to biology:

> "A new method of study. --Previous to Darwin's time the study of plants and animals, was carried on chiefly by observations in the field. The science was largely descriptive -a record of what men had observed under conditions over which they did not endeavor to exercise any control; it was accurately named "Natural History"- a description of nature. But Darwin and a few of his contemporaries, especially among botanists, began to make observations under conditions which they determined and largely regulated. In this way the problems were simplified, observation became more accurate, and the endeavor was made to assign the probable *causes* of the observed phenomena. With the introduction of this experimental method, science began to make rapid strides, and, more than ever before, facts began to be, not only recorded, but interpreted and explained" (Gager, 1916: 520).

He presents Mendel's experiments and conclusions almost as though he were reporting them in a scientific paper, using the typical headings of a journal publication. The excerpt below illustrates the style:

"The problem which he endeavored to solve was the law or laws 'governing the formation and development of hybrids,' with special reference to the laws according to which various characters of parents appear in their offspring"

"Mendel's method.--he recognized that, in order to solve the problem, attention must be given to at least three points, as follows: 1. 'to determine the number of different forms under which the offspring of hybrids appear ' 2. 'To arrange these forms with certainty according to their generations.' 3. 'To ascertain accurately their statistical relations,' that is, to express the results quantitatively. No previous student had recognized the fundamental importance of these requirements" (Gager, 1916: 550).

At the end of his chapters on evolution and genetics, Gager includes something that is more typical of review papers than textbooks; he comments on the state of the subject at that time. After describing evolution, he lists objections made by serious scientists:

"Objections to Darwin's theory were also brought forward by scientific men - partly from prejudice, but chiefly because they demanded (and rightly) more evidence, especially on certain points which seemed at variance with the theory. For example, they said, no one has ever observed a new species develop from another; this ought to be possible if evolution by natural selection is now in progress. The absence of "connecting links," or transitional forms between two related species was noted; the presence of apparently useless characters was not accounted for; and the geologists and astronomers claimed that the time required for evolution to produce the organic world as we now behold it is longer than the age of the earth as understood from geological and astronomical evidence . There is not space here to summarize the answers to all these objections. Suffice it to say that scientific investigation since Darwin's time has given us reasonably satisfactory answers to most of them, so that now practically no scientific man doubts the essential truth of evolution; it is the corner stone of all recent science, the foundation of all modern thought" (Gager, 1916: 518-519).

At the end of his chapter on genetics, Gager includes four unanswered questions that have arisen: *What is the mechanism of inheritance? How may dominance be explained? Are acquired characters inherited? Can the inheritance of a strain be artificially altered?* Neither Barrows in 1930, nor Keeton in 1967, includes the arguments against Darwin's theory of evolution, or a list of questions to be answered. By 1930 these arguments were no longer taken seriously, and fewer questions remained unanswered.

Gager's account, written so soon after Mendel's work was rediscovered, is detailed and uncertain. This makes his description both more realistic and more cluttered. For example, he describes Mendel's experiments with detail that would never be added today. He says:

"The edible pea is commonly self-fertilized; therefore, to make crosses it is necessary carefully to remove the stamens of one flower before the anthers have begun to shed their pollen, and then place pollen from one flower on the stigma. The flowers must then be carefully guarded, *e.g.*, by tying bags over them (Fig. 406), to prevent other pollen being deposited by insects or otherwise. In this way the experimenter knows just what characteristics enter into the hybrid. Careful record is kept of all data, and plants produced in this way, with ancestral characters noted and recorded, are called *pedigreed*. Plantings of such plants are called *pedigreed cultures*" (Gager, 1916: 552-553).

Similarly, Gager still believed that DeVries' theory of mutation was true, so his detailed explanation of it occupies 21 pages. Since these issues were still in dispute, Gager discussed all sides, showing just how complicated they were; thus further confusing students. Because he was not clear about the issues himself, his explanations are hard to follow. Later accounts are clearer and less detailed, but also less intense. Gager wrote about events he was immediately involved in, and Barrows, in 1930, wrote about events he remembered. This gives their accounts an appealing air of immediacy.

Genetics in 1930-1993. The major concepts of genetics were understood by 1920, so in 1930 Barrows presented the subject basically as textbook authors do today, giving clear explanations. The textbooks by Keeton (1967), and by Keeton and Gould (1993), use approximately the same approach to genetics as Barrows used in 1930. All three books describe Mendel's experiments and a modern interpretation of his results, multigenic inheritance, gene interactions, multiple alleles, mutations, sex-influenced characters, and linkage. Genetics is described by Barrows in 1930 in 37 pages, by

Keeton in 1967 in 41 pages and by Keeton and Gould in 1993 in 36 pages. It is almost as though a formula had been found before 1930 that allowed these concepts to be presented in the clearest and most concise manner. Once found, the formula has been repeated almost unchanged ever since.

However, there is a difference between accounts given in 1930 and today. Barrows mentions the mutation theory of DeVries, even though this theory had been discounted twenty years earlier, and Barrows no longer believed it was true. Similarly, Barrows describes the work of Galton and the controversy over discontinuous and continuous variation, and he explains how the misunderstandings were cleared up. When an issue that has been in dispute is finally resolved, textbook authors continue to mention the failed theory for some time because it still seems to be part of the fabric of the subject, even if it is no longer accepted as true. Later authors who did not live through the dispute do not mention unsuccessful theories, so they give a clearer and shorter, if less picturesque, account of the subject. The recent introductory textbooks do not mention DeVries or Galton.

Molecular biology in university textbooks

Early accounts. In 1957 the importance of DNA had just been discovered. Villee (1957) describes DNA in four pages, but he does not know much about it, and some of his explanations are incorrect. For example, he suggests that DNA might be directly responsible for imposing the external shape on a protein.

"According to current theory, genes act as catalysts for the production of enzymes. Enzymes are believed to owe their specificity to the specific configuration of the surface of the enzyme molecule. Only those substances whose molecules have the proper shape can fit on the surface of the enzyme, make contact at a number of points and form an enzyme-substrate complex. The surface of the gene is believed to have a comparable specific conformation and this specific conformation is transferred either directly or via an intermediate template to the enzyme. This theory requires that there be a separate gene for each type of enzyme, and there is quite a bit of experimental evidence which supports this view (Villee, 1957: 486).

When Keeton (1967) and Curtis (1968) wrote their textbooks, much more was known about DNA. By 1966 the structure of DNA, replication, transcription, translation and the genetic code were all understood in outline, but this understanding was very recent. These early descriptions are written more as review papers than chapters in textbooks. Detailed descriptions are given of the discovery of DNA, evidence is given to support statements about DNA, and important experiments are described in considerable detail.

Just as it was hard for Barrows (1930) and Gager (1916) to leave out the details of events they had recently lived through, so it seemed hard in 1967 to leave out details of the first experiments in molecular biology. For example the first version of Keeton's text (1967) gives an extensive description of the experiments of Beadle and Tatum on *Neurospora* (done in the 1940s) as evidence that genes determine the sequence of amino acids in a protein. This includes a detailed explanation of why *Neurospora* is a good experimental organism, how mutations were induced with x-rays, how spores are produced in *Neurospora*, and how *Neurospora* can be grown on minimal media with certain vitamin and amino acid supplements. There is a page of diagrams showing the experimental procedures used, and the experiments are described in detail. The work of James Sumner of Cornell University is also described, and details are given about apparent exceptions to the one gene - one enzyme model. This section is five pages long in the first edition (1967) of Keeton's text, and it contains many complex concepts. The fifth edition (1993) of the text does not even mention the work on *Neurospora* or the one gene - one enzyme hypothesis. Perhaps this is because there is now overwhelming evidence that genes determine the amino acid sequence of proteins so it is assumed that it is no longer necessary to present evidence; the process is simply described. Once the complicated description of the experiments of Beadle and Tatum are removed, only one concept remains, and there is room for new concepts and details of more recent experiments.

The first editions of these early textbooks give quite different accounts of molecular biology. Curtis (1968) covers approximately the same story as Keeton (1967), but she describes things in a different order, beginning with a chapter called "Molds and microbes" in which she describes the relationships between genes and enzymes. Orians (1973) does not even put the chapter on DNA near the chapter on heredity, as the others do. Instead, he places it in a section on information and locates it next to nervous systems. He spends less time discussing the genetic code than Keeton does, and less time on bacteria and phages than Curtis does. Instead, he emphasizes the experimental work that resulted in the genetic code. Here he goes into enormous detail, introducing many extra concepts in the process. For example, in explaining how scientists developed cell-free systems for determining the role of RNA in protein synthesis, he says:

> "All bacteria apparently contain the enzyme polynucleotide phosphorylase which catalyses the reaction: RNA + P $\rightleftarrows$ ribonucleoside - P ~ P
>
> Under normal circumstances, the equilibrium of this reaction lies far to the right, but if a cell-free system is loaded with high concentrations of nucleoside diphosphates the enzyme can be made to catalyze the formation of synthetic RNA molecules. The composition of this RNA and the proteins whose synthesis it directs, as an artificial mRNA, depends solely upon the composition of the ribonucleoside diphosphates added. If two or more diphosphates are added, the base sequences are determined randomly according to the relative concentrations of the diphosphates. For example, if adenosine and uridylic acid residues are used, the triplets will be AAA, AAU, AUA, AUU, UAA, UAU and AUU, their proportions depending upon the ratio of A to U. These mixtures cause the incorporation of more amino acids into RNA than in pure solutions, but the exact order of the nucleotides in the triplets cannot at present be determined.
>
> Other techniques have been developed to solve this problem. Biochemists have been able to synthesize polyribonucleotides with known repeating sequences which direct the formation of amino acids into polypeptides. The copolymer UGUGUGUGU comprises a series of triplets in which UGU and GUG alternate. It directs the synthesis of polypeptides containing the amino acids cysteine and

valine. Also, techniques for binding single ribonucleotides to a ribosome have been developed and many codons have been determined in this manner. Thus, in little more than a decade after Watson and Crick proposed their model for DNA, the basic features of the genetic code have been determined" (Orians, 1973: 392-393).

These early descriptions of molecular biology all contain this kind of experimental detail, but the particulars vary from book to book. Later texts leave out the details of early experiments, simply summarizing the important concepts and adding more recent concepts.

All of the early accounts of molecular biology are (like Gager's account of genetics) similar to review papers. They present a fairly complete description of the important developments and experiments in molecular biology, and they present evidence for each concept, as though the students were scientists, judging the truth of the concepts. For example, Keeton (1967) gives evidence that RNA and ribosomes are intermediaries in protein synthesis. Later editions of these texts no longer assume that evidence is needed, or perhaps the evidence is so abundant that it would be difficult to choose which evidence to present.

The treatment of molecular biology in textbooks has followed the same pattern as the treatment of genetics. The similarity of recent accounts suggests that, by 1985, a formula had been found for explaining DNA structure and function. The recent editions of four text books (Villee, Solomon and Davis, 1985; Curtis and Barnes, 1989; Keeton and Gould, 1993; and Purves, Orians and Heller, 1995) give basically the same explanation for molecular biology and present the same topics, in the same order, with the same level of detail. They begin with a short history of DNA, mentioning only a few of the scientists involved in its discovery (Griffith, Avery, Hershey and Chase). Then they describe DNA, with diagrams of the double helix, showing how the bases pair with each other. They describe how Watson and Crick developed their model of DNA (including an X-ray photograph of DNA and a photograph of Watson and Crick standing by their model). Next, they describe the mechanisms of DNA replication, including the Meselson-Stahl experiment showing semi-conservative replication. All four books describe transcription and translation in a new chapter; this begins with transcription, followed by a description of different kinds of RNA, and the mechanism of protein production. Finally they describe the genetic code, explain mutations, and discuss repair mechanisms in cells. All four books have separate chapters on gene regulation and the modern uses of molecular biology (genetic engineering). Only the chapters on gene regulation and genetic engineering vary from one text to another, presumably because these subjects are much more recent than transcription and translation, so the formula for explaining them has not yet been found.

Increased efficiency and clarity of accounts. It is often argued by educators that science is progressing so fast that nobody can remain up-to-date (Schwab, 1962; Glass, 1970).

> "The biological sciences are now advancing so rapidly that with every ten to fifteen years there is a doubling of our significant knowledge. This fact makes imperative a frequent reappraisal and wholesale revision of existing curriculums.

It also makes it increasingly difficult to cover in any satisfactory way all that is significant and all that a general citizen should know about these sciences" (Glass, 1964: 95).

In the descriptions of genetics in 1916 and 1930 above, the concepts became clearer with time, and they were explained more efficiently in 1930 than in 1916. Even after 1930, the explanations became more concise because details that seemed important close to the event no longer seemed relevant later, and were left out. This left room to add new concepts. The same thing can be seen in molecular biology. If there is a knowledge explosion, surely it must be seen in molecular biology, about which at least 10-100 times more information is known today than 25 years ago. We would expect chapters on molecular biology to also be 10-100 times larger but they are not. Table 2 shows that chapters on molecular biology are only marginally larger today than they were 25 years ago. Perhaps what we believe is crucial knowledge for an understanding of a subject changes with time. When the knowledge is new to the scientists and teachers, all the details seem relevant to an understanding of the topic. However, after some time, many of the details and evidence no longer seem crucial, and the clutter of details even seems to detract from the clarity of the explanation.

The pages devoted to genetic engineering in the new editions cover entirely new topics so they contain additional information, but the chapters on DNA replication, transcription and translation are also new to a large extent, since so much has been learned about them since 1967.

Table 2. Number of pages devoted to molecular biology shortly after the discovery of DNA and today. Modern texts contain chapters on the original topics of molecular biology (DNA replication, transcription and translation), but they also contain chapters on gene regulation and genetic engineering, (totally new topics).

Author	Early editions of text		Later editions of text		
	DNA replication, transcription & translation		DNA replication, transcription & translation		Gene engineering gene regulation
	Year	No pages	Year	No. pages	No. pages
Villee	1957	4	1985	41	30
Keeton	1967	39	1993	48	21
Curtis	1968	59	1989	58	43
Orians	1973	17	1995	48	42
Average		38*		49	34

*Omitting Villee (1957).

Why, then, are these chapters only an average of 11 pages longer than books written 25 years ago, and why has the number of new concepts to be learned not increased? The answer becomes clear if we compare the texts by Keeton (1967) and Keeton and Gould (1993). The 1967 edition describes the work of 40 individual scientists, in detail. The 1993 edition describes the work of only 20 scientists, with fewer details about their experiments. In 1967 there is a five-page description of the work of Beadle and Tatum, but that is not mentioned in the fifth edition. The evidence that RNA is involved in protein production is presented in two pages in 1967 but is omitted in 1993. Three pages more are used to explain the genetic code in 1967 than in 1993. These omissions leave more room in the new edition for new issues and mechanisms. These new explanations are not any more detailed and they contain no more new concepts than the earlier editions of the textbooks. Students today are learning the same number of concepts and details; they are just learning some different concepts and details, as suggested below:

> "As we understand subjects better we are not teaching more, we are just teaching better and students are not learning more, they are just understanding better" (L.C. Vining, Dalhousie University, personal communication).

The knowledge explosion is not a problem; as subjects are better understood, there is not more to learn; what is learned is presented more clearly and concisely. However, subjects become less intriguing once they have been understood for a long time. It seems impossible to recapture the excitement that comes with not quite knowing the final answers.

Common patterns

Even though the breakthroughs in evolution, genetics and molecular biology occurred at different times, they have been handled, first by researchers, then by educators, in similar ways. Each breakthrough was followed by an initial period of controversy and confusion before the most important issues were accepted by most of the scientific community. In all three fields of study, the basic concepts were rarely mentioned in textbooks until after they had been accepted by the scientific community. DeVries' theory of mutation is an exception. It was described in many textbooks before 1910 although it turned out to be incorrect. Even after subjects like Mendelian genetics or molecular biology are accepted by the scientific community and described in textbooks, these accounts are confusing for some time and accounts in different textbooks vary. Later, as authors become more comfortable with the concepts, and an efficient explanation has been developed, the variety of presentation disappears and explanations become more effective and economical.

The Organization of Textbooks

The organization of subjects in biology textbooks has evolved to reflect the changes in biology as a discipline, but in some cases it also shows the influence of theory in education. The first five approaches, described below, are related to the structure of biology and demonstrate the emphasis favoured by biologists. By 1930 most high school texts were written by educators, and some books were written to emphasize the usefulness of biology to society. The kinds of organization are:

A. Organized around biology

1. **Classification.** The earliest texts were organized around the classification of organisms and they described superficial features like flower structure because this was the basis of classification. Dawson's book on zoology, published in 1870 but used in Nova Scotia until 1899 was organized around classification.

2. **Survey of the phyla--illustration of evolution** Most books used after 1858

were organized to illustrate the theory of evolution. They emphasized the similarities and differences between organisms and assumed that these were determined by evolution. Many books presented a survey of the phyla of organisms moving from the simplest to the most complex in a way that imitated evolution. This organization looks superficially like that used to teach classification but it emphasized the underlying features that were fundamental to the organisms and their evolution, rather than superficial structures used to identify organisms.

3. **Types approach** This approach, proposed by T.H. Huxley, and described earlier, was similar to the one given above but was developed specifically to help students learn. The method begins with a common animal, usually a vertebrate like a rabbit, and describes structures and functions to give the student a view of the whole animal. T the author gradually moves to other groups and compares a representative member of each group with the original familiar animal. The types approach implicitly deals with evolution because it moves through the major groups and brings out the differences among them. However, it also gives comprehensive pictures of the structure and function of individual organisms. In the nineteenth century this approach emphasized morphology, but in the twentieth it increasingly emphasized physiology.

4. **Physiology approach** With this approach, each of the organ systems (digestion, circulation, excretion, nervous, locomotion, reproduction) is described in turn, and the evolutionary changes that have occurred in that system are given. For example, the digestive system is explained, then examples of different kinds of digestive systems are described. This approach is similar to the types approach in what is ultimately

learned, but it is organized around organ systems, while the types approach is organized around individual organisms.

After 1900, experiments, function and physiology took over from observation and morphology, so the physiological approach gained popularity in classrooms. More stress was laid on understanding the parts of organisms rather than whole organisms and this reflected the move in biology to working with smaller problems that were more likely to be solved. The physiology approach was adopted increasingly after 1920.

5. **Principles approach** Most modern textbooks are organized, not around individual organisms, but around the common principles that govern all life: cell structure, metabolism, genetics, evolution, and ecology. These features of biology operate at levels other than the level of the individual organism: at the molecular, cellular, population and community levels. This scheme has increased steadily since 1950.

B. Organized around social issues

6. **Human biology** Human biology (digestion, circulation etc.) is described in detail. General principles of biology are discussed largely as they relate to humans. Courses in human physiology were taught in grade 11 until 1920, but then physiology was integrated into general biology.

7. **Practical applications of biology - the use of biological knowledge by society** Some school textbooks emphasize the practical applications of biology; they are organized around social issues rather than biology itself, and biology is used as background for the social issue. This method has been used off and on throughout the

period of public education. I will describe it in more detail in Chapter 4.

Combinations of Approaches

Since 1900, most textbooks have not been organized totally around one of the choices given above. Most authors organize different parts of the book around the different approaches. Appendix 3 contains a list showing the proportions of textbooks devoted to different topics and approaches, and Figures 1, 2 and 3 summarize the results.

Which concepts are left out of the curriculum?

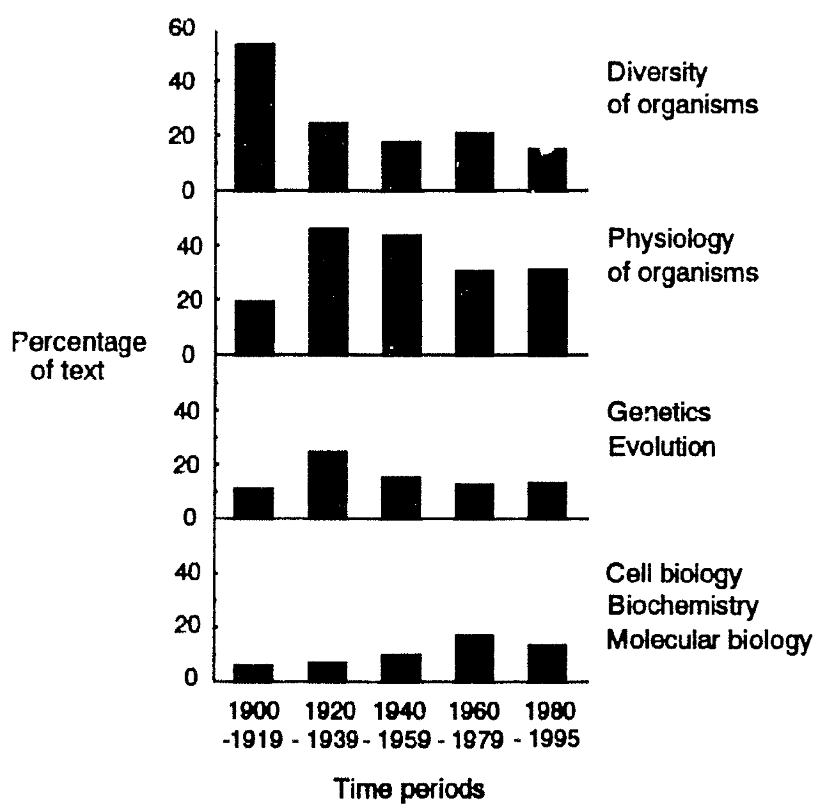
If genetics, taught in 1930, is virtually the same as genetics taught today, and yet molecular biology has been added, something must be left out. It is true that textbooks have become larger (See Table 3), and some of the increase in size has resulted from the addition of new topics like behavior and immunology, as well as molecular biology, biochemistry and ecology.

Table 3. Textbook size over the last century

Time period	Total number of pages		
	University	Grade 12	Grade 10
1900-1919	450	469	241
1920-1939	518	513	336
1940-1959	698	562	579
1960-1979	723	703	632
1980-1995	1044	720	772

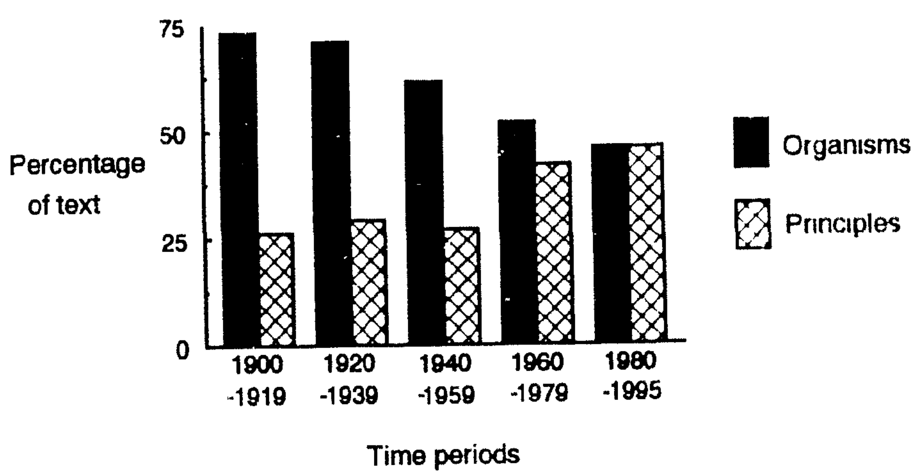
Modern textbooks also have a new, less dense format, with more diagrams than early textbooks. However, different subjects are emphasized today than fifty years ago. The subjects taught now reflect the modern approach to biology. As new subject areas and approaches appeared, they took increasingly large percentages of the text. Molecular biology did not replace genetics, but it did replace other topics like plant and animal phyla, and comparative animal physiology. Figure 1 illustrates the change in emphasis in university textbooks this century.

Figure 1. Proportions of university textbooks devoted to different topics averaged over twenty year period during the twentieth century. Topics are listed at the right.



From 1900 to 1920, most university textbooks concentrated on diversity of organisms. From 1920 to 1940, physiology of organisms more than doubled and diversity of organisms decreased by the same proportion. At the same time, there was a doubling of genetics and evolution, as these subjects became well established. Between 1940 and 1960, these subjects remained stable in the curriculum. Molecular and cellular biology were given more emphasis, but little was known about them, so they still formed a small percentage of the textbook. Since 1960 there has been a steady increase in the proportion of the text devoted to biology at the molecular and cellular level and a proportional decrease in biology at the level of the individual organism. This trend can be seen more clearly in Figure 2.

Figure 2. Percentage of university introductory biology textbooks devoted to biology of organisms and the unifying principles of biology during the twentieth century. The category "organisms" includes diversity of organisms and physiology. Principles includes cell biology, biochemistry, molecular biology, genetics, evolution and ecology.



During the first two decades of this century, about 75% of a textbook discussed issues at the level of individual organisms and 25% discussed the general principles of biology. These proportions remained approximately the same until after 1960, when more emphasis was placed on principles and less on organisms. This change has increased since 1960 so that approximately 50% of modern textbooks is devoted to each of these aspects of biology and this trend toward an increase in general principles and a decrease in individual organisms is likely to continue.

Chapter 3

The Influence of Education on Science Education before 1950

Herbert Kliebard (1986) has identified four groups that influenced the curriculum from 1893-1958: the humanists, who represented the status quo, and three groups of reformers: developmentalists, social efficiency educators and social meliorists. Each group of reformers had a different conception of the curriculum, but they used similar words to describe their reforms, so they were confused with each other, and all were eventually called "progressive." The groups, in more detail, were:

Humanists (subject-centred educators) were associated with colleges. They wanted to teach the finest features of western culture, and they supported two basic features: the claims of the disciplines, and the need to ask students to work hard in school. They were against specialized vocational training. Their influence in high school education diminished after 1900.

Developmentalists (or child-centred educators) romanticized children and wanted to allow them to decide what to learn for themselves. The developmentalist movement of the late nineteenth century created a curriculum around developmental stages of children. "Child-centred" is a better name for the general movement that has lasted because it reflects the focus on the student that has been central in this basic approach for over a century. The influence of the child-centred movement on the school curriculum has been increasing since 1920.

Social efficiency educators wanted to create an efficient education that would mold children for their roles in society. Efficiency was an aspect of this movement because people were to be taught only what they would use directly as adults. Waste could be eliminated by deciding on the future of an individual, and educating him specifically for that. This was just another way of educating according to social class. Boys who would eventually work in factories were given a technical training rather than an academic education, and girls who would become homemakers would be given a different training than boys. This rationale fit well into the new industrial society and mechanistic philosophy in the early twentieth century. The principles of social efficiency dominated education from 1910 to 1930. It was a narrow, practical, approach that was basically anti-intellectual, and did not value culture (DeBoer, 1991; Kliebard, 1986).

Social meliorists originally developed as a group who opposed social Darwinism, arguing that it was a corruption of Darwinian theory. They felt that human beings are not susceptible to the forces of nature because they can intervene to ensure social progress (Kliebard, 1986). Later the social meliorists believed that the schools should be used to improve society, not to maintain the status quo. Some educators, including John Dewey, supported this approach. This goal did not lead to obvious changes in the science curriculum but it probably kept the social efficiency curriculum in check, and the idea gradually developed from it that schools should teach students to be critical of society. This philosophy was behind the idea of a welfare state.

Kliebard argues that, throughout this century, these four groups have tried to control the curriculum. No single group gained complete control, but during some periods certain groups had greater influence on the curriculum than others. Occasionally there were alliances between them. For example, alliances between the child-centred and social efficiency movements determined the curriculum from 1930 to 1960, and an alliance between the child-centred and the subject-centred supporters led to the short-lived reforms in the science curricula in 1960. The curriculum has resulted from a blend of approaches, at one time moving in one direction, and at another time in a different direction.

Nineteenth century education

The humanist, or subject-centred, approach dominated education in the nineteenth century because the high school curriculum was controlled by professors in universities. Experts in education call this the period of "college domination" (Downing, 1925). University biologists wrote the school textbooks and set provincial examinations so the biology curriculum reflected biology as it was seen by scientists. Science was introduced as a school subject in the nineteenth century; initially there were no school laboratories and teachers used methods that were more appropriate for classics than science. However, in the late nineteenth century, there was considerable discussion about teaching methods and learning, and most of the ideas popular in science education today were introduced before 1900. Our image of the rigid Victorian system is not evident in the approaches used in textbooks of that time or the methods advocated by those who wrote about education (Westaway, 1929). By 1900 science classes usually included laboratory work, child-centred approaches to education were becoming popular, and the advantages and disadvantages of inquiry learning were actively debated.

The ideas discussed by educators in major world centres were brought to the teachers in Nova Scotia by the *Journal of Education*, published each month by the Department of Education for Nova Scotia. It contained practical information like schedules for final examinations and curriculum guidelines needed by teachers, but it also contained many articles about education, some written by local teachers or professors, and others copied from the speeches or articles of famous educators.

The theory of instruction developed by Johann Herbart in 1806, with emphasis on the student rather than the subject, became popular in America in the late nineteenth century. Some parts of this theory are also echoed in more modern theories of education. It was common then to view the mind as a set of faculties, like reasoning power and memory, that could be developed by practice. Herbart disagreed with this, and believed instead that the mind consisted of ideas and concepts that each person formed from scratch. The purpose of instruction was to help each student construct a series of ideas that could build on each other. Each idea or concept should be included in the curriculum only if it was useful for the individual. For example, memorizing the names of plants and animals was not considered worthwhile if the information would not be useful later, because the act of memorizing would do nothing to develop the mind.

Herbart proposed a method of teaching that focused on the student rather than on a logical presentation of the discipline. First the interest of the student had to be stimulated. Next students were allowed to discover whatever they could for themselves. Each new idea was then placed in a context of larger generalizations and principles, and it was also linked with what the student already knew. Then the teacher gave direct instruction to the pupils, systematically explaining concepts that students could not discover alone. The teacher was expected to teach skilfully and attractively, showing enthusiasm and personal interest in the subject. Finally, pupils would demonstrate that they had acquired the knowledge by solving problems (DeBoer, 1991: 27). These steps are remarkably close to those used today in the construction of a lesson.

Some of Herbart's views were echoed in a paper printed in the *Journal of Education* (Nova Scotia) in 1870 and written by J. M. Wilson, a mathematics and natural science master at Rugby School. Wilson said that teachers must always build on what a student already knows: "It is to his existing knowledge and to that alone that you must dig down to get a sure foundation" (Wilson, 1870: 486). The teacher must systematize, arrange and extend that knowledge. He describes, with a delightful Victorian flourish, what will happen if teachers do not follow this advice:

> "Rapidly knowledge crystallizes round a solid nucleus; and anything the master gives that is suited to the existing knowledge is absorbed and assimilated into the growing mass· and if he is unwise and impatient enough to say something which is to him perhaps a truth most vivid and suggestive, but for which his boys are unripe he will see them, if they are really well trained, *reject* it as the cock despised the diamond among the barley (and the cock was quite right), or still worse, less wise than the cock, swallow it whole as a dead and choking formula" (Wilson, 1870: 486-487).

Laboratory Work. In 1850 there were few student laboratories in schools or universities; instead teachers gave demonstrations at the front of the class. However, scientists universally wanted to include laboratory work in schools. Thomas Huxley made some of the most persuasive arguments. Practical activity would allow students to see the phenomenon for themselves, and when this was linked with knowledge obtained from lectures and books, they would be able to build their own concepts. Huxley said:

> "If a man wishes to be a chemist, it is not only necessary that he should read chemical books and attend chemical lectures, but that he snould actually perform the fundamental experiments in the laboratory for himself, and thus learn exactly what the words which he finds in his books and hears from his teachers mean. If he does not do so, he may read till the crack of doom, but he will never know much about chemistry" (Huxley, 1898: 281-282).

By 1890 universities asked for laboratory work as part of their entrance requirements, and in 1892 the Committee of Ten (an influential committee appointed to make recommendations about high school education) recommended that sixty percent of class time should be spent in laboratory work (National Education Association, 1892). Most textbooks integrated laboratory assignments into the text. The arguments in favour of laboratory work had been won by scientists by 1900--only to be partially overturned during the progressive era.

Inquiry Learning. Henry Armstrong, a British chemist, publicized the heuristic method (inquiry learning) near the end of the nineteenth century (Van Praagh, 1973). His strong advocacy of this method stimulated much debate and many of the advantages and disadvantages of inquiry were clear to teachers by 1900. In 1870 J.M. Wilson (quoted in the *Journal of Education*, 1870) urged teachers to give students the impression that they were discovering for themselves. He did not name this teaching method, but he described guided inquiry in detail.

> ".. as often as possible to give them the pleasure of discovery. He (the school master) may guide them to the treasure, but let him unselfishly give them the delight of at least thinking they have found it. This is the charm that tempts them on, and is the highest reward they can win" (Wilson, 1870: 487).

The passage below is an excerpt from a long description of the use of guided inquiry in a botany class:

> "Suppose then your class of thirty or forty boys before you, of ages from 13 to 16, as they sit at their first botanical lesson; some curious to know what is going to happen, some resigned to anything, some convinced that it is all a folly. You hand round to each boy several specimens, say of the herb Robert; and taking one of the flowers, you ask one of them to describe the parts of it. "Some pink leaves," is the reply. "How many?" "Five" "Any other parts?" "Some little things inside." "Anything outside?" "Some green leaves." "How many?" "Five." "Very good." Now pull off the five green leaves outside and lay them side by side; next pull off the five pink leaves, and lay them side by side; and now examine the little things inside. What do you find?" "a lot of little stalks or things." "Pull them off and count them:" They find ten. Then show them the

little dust bags at the top, and finally the curiously constructed central column, and the carefully concealed seeds. By this time all are on the alert. Then we resume: the parts in the flower are, outer green envelope, inner coloured envelope, the little stalks with dust bags, and the central column with the seeds. Then you give them all wall flowers: and they are to write down what they find; and you go around and see what they write down. Probably some one has found six "*storks*" inside his wall-flower and you make him write on the blackboard, for the benefit of the class, the curious discovery, charging them all to note any accidental varieties in feature; and you make them very minutely notice all the structure of the central column. Then you give them all the common pelargonium and treat it similarly; and by the end of the hour they have learnt one great lesson, the existence of the four whorls, though they have yet not heard the name" (Wilson, 1870: 487-488).

Most teachers recognized the appeal of inquiry, but many also recognized the difficulties associated with it, and supported a more moderate approach that used it as only one phase of teaching (Wieman, 1916). Some of the difficulties identified in 1908 by Alexander Smith and Edwin Hall, university science professors who were members of the Committee of Ten, were: it takes too much time, it does not furnish enough knowledge when used by itself, the laws of chemistry and physics are too difficult for pupils to discover independently, students are expected to make too much of a jump--the questions they are asked could not be answered from the observations they can make in class, and the attempt often leads to frustration (DeBoer, 1991). Many teachers preferred a guided approach, between the extremes of verification and inquiry. Students are given problems to solve, but these are not problems that ask students to discover important concepts. In addition the teacher does not mislead himself and his pupils by making them think they are discovering important concepts (DeBoer, 1991: 60).

Inquiry seems to have had the same effect in the early twentieth century that it has now. This comes out nicely in the two statements below:

> "Still, 'the spirit of inquiry' should most certainly be encouraged, and should run through any course of science teaching. By all means get boys interested in common occurrences, and lead them to follow up clues as to possible causes" (Westaway, 1929: 27).

and

> "One cause at least of the unsatisfactory conditions in secondary science teaching has been the tendency to over-emphasize *method* to the detriment of *careful observations* on *carefully chosen material*. Any system of teaching which fails to recognize the essential unity of these two things will fail to accomplish the highest ends in science teaching" (Wieman, 1916)

Very little has been said about inquiry learning in the last 35 years, that was not said just as well before 1930.

Biology in schools. Certain textbooks were popular throughout North America because they were so well written. For example, *The Essentials of Botany*, used in grade 12 botany in Nova Scotia from 1893-1909, was written by C.E. Bessey, an American professor of botany who sat on the Committee of Ten. Bessey integrates theory and laboratory work in each chapter. For example, while describing cell structures he tells students (in a two-page section) how to make sections of root tips, stain them and examine cells with a microscope (microscopes then cost $25-$30).

Educational reform during the first half of the twentieth century

The rise of the social efficiency movement

The social efficiency movement had its greatest influence from 1910 to 1930. After 1920, children were streamed either into a traditional, discipline-oriented curriculum that led them to university, or into a commercial or industrial program that trained them in job skills. Junior high schools were supported by the social efficiency movement as a way of streaming children (Kliebard, 1986: 125). General science courses were taught (in Nova Scotia from 1930-1960) to give a practical introduction to science, on the assumption that this would be the last science course taken by many students. These general science courses were organized around the practical applications of science rather than around science itself. One of the textbooks used in Nova Scotia (*General Science* written by Snyder in 1925) contains chapters on airplanes, heating a home, makeup, weather, etc. Science was used in these courses as background explanation so there was little chance to develop a comprehensive understanding of the discipline.

The leaders of the social efficiency movement in education were teachers, school supervisors and professors of education. By 1911 they were protesting against the discipline-oriented view of science and recommending changes. A committee set up by the National Education Association (NEA) to examine science education submitted a report in 1920 called *Reorganization of Science in Secondary Schools*.

The preceding major committee charged with examining education (Committee of Ten, 1892) contained 50% scientists and each of the subcommittees was headed by a scientist. Between 1893 and 1920 both the composition of the committee examining education and the image of science education changed. The *Committee on the Reorganization of Science in Secondary Schools* contained only 23% scientists and each of the subcommittees was headed by a teacher or an expert in education. The 1920 committee was headed by a Professor of Education at Columbia University Teachers College (Hurd, 1961). The justification for science in the curriculum shifted between 1893 and 1920 from science's ability to develop students' intellectual skills, to science's ability to make students into useful members of society. This difference in the view of science education was at least partly caused by the loss of control by scientists over science education as the teachers colleges exercised greater influence over education in schools. There was a general sense within society that the "University domination" over education should end. The 1920 report recommended that high school science courses should not be organized in terms of the logic of the discipline. Instead they should start with questions that concerned the pupil's own life and should be organized around questions, problems and projects that would give the student more activity. More attention should be given to topics related to local communities, school activities and local industries. The point was to understand biology in relation to health and agricultural production (Hurd, 1961: 35-36).

Humanist values were ignored as the universities became isolated from high school education, but university professors did not complain as long as the traditional academic curriculum was retained for students going to college. However, the approach spilled over into all courses, so even the academic courses were oriented more toward practical applications.

Education for social efficiency was supported by two developments in psychology: intelligence quotients, which allowed schools to label children and justified placing them in technical programs, and Thorndike's conclusion that there was no transfer of learning. It is generally assumed that we can use (or transfer) what we learn in school to new situations. However, there has always been disagreement about how much transfer takes place and in which contexts. Thorndike said that students can use only what they are taught directly, and this view supported proponents of the social efficiency program:

> "It is apparent that many pupils who are exposed to or have studied, the traditional physics and chemistry offered in the typical secondary school in the United States show very little transfer of this knowledge to their daily living. We find that after the study of these subjects the average girl makes no improvement or modification in her method of washing dishes or clothes, in general house cleaning or in cooking. The functional course in science should definitely effect more efficient living on the part of not only the brighter pupils but also on the average and subnormal children" (Hoff, 1947: 66).

Deciding what to teach. Curriculum development had been easy when courses were discipline-oriented, but it became more complicated after 1920 when decisions were based on other factors. Supporters of the social efficiency movement believed that the "scientific" way of determining the curriculum was to analyse what information adults needed to do their jobs (Downing, 1925; Hoff, 1947). In one study, several thousand women were questioned to find out what skills, interests and knowledge they needed for their daily household activities. A biology education should produce adults who can read the newspaper, so newspapers were surveyed in another study to see what biology subjects were mentioned. The researchers read eleven daily newspapers for 2 months in 1921 and recorded the amount of space (in inches of newspaper column) devoted to various topics. They found that 7,540 inches were devoted to health, 6,422 to animals, 5,521 to plants, 4,024 to food. Supporters of the social efficiency movement applauded this kind of study (Downing, 1925).

Increasing Influence of the Child-Centred Approach

The mechanistic philosophy that dominated in the early twentieth century was expressed in education as the social efficiency movement, but it gave way after 1920 to the holistic approach that viewed society as an integrated structure in which balance was required. The holistic approach was reflected in education as the increased influence of the child-centred movement and the rise in social meliorism. By 1930-1940 the child-centred approach flourished in the form of the project, or problem-solving method, which dominated science education during the progressive era.

Problem-solving as a teaching method

Problem solving was always used to help students learn, but in the early twentieth century a teaching method called the "project" or "problem" method was defined. It was probably an American version of the British heuristics movement. With this approach, the problem (rather than the subject matter) unified what was learned; student laboratory activities were to be organized around definite, well-chosen problems (Twiss, 1914). The description of the problem method below could have been written about the heuristics method, or later about discovery learning.

> "With the problem as the unit of instruction, the pupil goes to the laboratory to make an experimental test of an hypothesis which he has set up in the process of thinking on a problem. He is in the attitude not of 'doing a stunt' nor yet of 'fixing a principle in mind,' Rather he is in the attitude of an inquirer eager to find an answer to a question, and putting the question up to nature herself. He goes there to get information direct from nature, just as the scientist does when he cannot find it in the works of other scientists. Since however, he is not experienced enough to work independently as the scientist does, the teacher is present as his helper, inspirer and guide. (Twiss, 1914: 460).

The project. Projects were one kind of problem but the term "project" went through a variety of definitions.

The original home project. By 1900 home projects were used in agriculture courses to encourage students to apply what they learned in school to their family farm.

For example, in a home-project, a student could weigh the cow's rations and calculate the cost for feed, or study the effect of changing the kind of feed. In 1899 the *Journal of Education* printed a letter written by an unnamed teacher in rural Nova Scotia who explained how he used agricultural projects in biology classes to give students practice in conducting experiments and using scientific methods. Each boy was given a package of seeds to plant with three objects in view: experimenting on growing a crop, studying the growth and structure of a particular plant, and studying the enemies of plants including weeds and insects. The experiments differed from student to student:

> "One may make a variety test of the onion to see what one of set varieties is best adapted to this locality. Another will study the effect of deep and shallow planting of seeds. Another the effect of frequent and rare cultivation. Another the advantages of a new method of potato culture. Another the differences in fertility of soil at different depths--with the causes including capillarity, solubility of plant food, and evaporation. All will be required to keep a careful record of their work from planting to harvesting, and be expected to add something to the stock of knowledge previously held. The second division of the work will be botanical, the students studying the plant from seed to maturity. The third will include the ordinary Nature work on insects and a comparison of other plants (weeds) with the particular one studied" (*Journal of Education, April 1899:* 77-78).

This kind of project was successful because it made students more interested in their school work and gave them a problem to solve. Farm projects were used, not just in agriculture courses but also in science classes, to make science seem more interesting. These projects had two essential features: they were done at home, and they allowed students to apply classroom knowledge to real situations (Kliebard, 1986).

A social efficiency redefinition of project. Members of the social efficiency movement liked projects because students were doing in school what they would eventually do as adults. However, they changed the role of the project by using it to replace other teaching activities rather than supplementing them as a home activity. In addition, they changed the definition of project from "solving a problem" to "an activity." One of the leaders of the social efficiency movement defined a project as:

> "A unit of educative work in which the most prominent feature is some form of positive and concrete achievement. The baking of a loaf of bread, the making of a shirtwaist, the raising of a bushel of corn, the making of a table, the installation of an electric-bell outfit--all of these, when undertaken by learners, and when so handled as to result in a large acquisition of knowledge and experience, are called projects" (Snedden, 1916, quoted in Bossing, 1942: 557).

The child-centred approach to the project (yet another redefinition). In 1918 William Kilpatrick gave the project a child-centred slant and extended the idea of project from practical subjects like agriculture to all subjects and to learning generally. Students were to learn all subjects by solving interesting problems (projects). A project could be almost anything: "building a boat, ... writing a letter, ... enjoying an experience such as listening to a story, ... solving some problem, ... learning the irregular verbs in French" (Kilpatrick, 1918: 16). However, there were definite criteria for a project; it should be a "wholehearted purposeful act carried out amid social surroundings." All coercion must be removed because students learn better when they carry out activities they define for themselves (Kilpatrick, 1918: 5). The project became any activity that a student carries out with some purpose in mind and with some degree of enthusiasm.

Kilpatrick also redefined the curriculum in terms of the project. ' . subject matter was no longer the material to be learned. Now children learned what emerged from their projects and subject matter was just a tool to help them learn. As he extended his concept of the curriculum Kilpatrick explained that the world is changing so quickly that children face an unknown future. We can prepare them for these changes by teaching them how to solve problems rather than just learning today's knowledge (Kilpatrick, 1932, *Journal of Education*). This approach became known as the "activity curriculum" or "experience curriculum".

The project curriculum was popular by the 1930s and the following example of a problem used in an experience curriculum was given in a book about biology teaching:

> "For example, let us suppose that during the study of heredity a student discovers that albino corn seedlings have some green spots developing upon the white blades. His interest is aroused and examining them more carefully he discovers that these spots can be rubbed off but will return in a few days. He uses a microscope and finds them to be a growth of mold. Recalling a similar growth in the tumbler which he used in watering the plants, he seeks a microscope and finds them to be a growth of mold. This leads to a study of sterile technics and a study of fungi and the plant diseases caused by them. The original problems

of rearing albino and green corn seedlings for heredity initiates a series of problems resulting in a project for this student on molds and plant diseases" (Miller and Blaydes, 1938: 45)

The problem approach had supporters in Nova Scotia. Among them was J.H. Fitch (Professor of general science, Provincial Normal College, Truro), whose article in the *Journal of Education* in 1932 stressed that the problem must lie within the range of experience of the students if it is to be effective. Professor Fitch adopted the idea of John Dewey that although problems should begin within the understanding of the students, they should extend the understanding beyond what the students know, into the range of science (Fitch, 1932: 69). He anticipated guided inquiry by suggesting that problems will not always arise in a spontaneous manner so the teacher may have to guide students to appropriate problems, and he gave an example:

"The problems that arise in spontaneous manner are too uncertain for the teacher to depend on them. He cannot wait until a pupil becomes curious about something before teaching a lesson on it. Fortunately the teacher is not without resources. For example, a teacher committed a class to the opinion that water always runs down hill. She then showed them a siphon in operation, when it appeared that water was behaving in the opposite way. The pupils had no rest until the difficulty was removed- It should be quite clear that a problem "out of the blue" was not the kind considered here. A problem having no familiar elements leaves a pupil quite helpless and indifferent" (Fitch, 1932: 69).

A number of people criticized the problem approach. It was argued that learning was incidental to doing the project and that it was hard to find appropriate projects that involved important concepts (Goetting, 1942). But the most serious problem with this approach was that it did not challenge students enough. In an article called "On making things too easy" printed in the *Journal of Education* in 1931, the authors (who were not named in the article) quoted Aldous Huxley:

> "Advanced schools (and in this respect almost all American schools are on the 'advanced' side) seem to be haunted by the notion that everything is too difficult. 'Poor children!' (A misplaced humanitarianism causes the voice to tremble with emotion.) 'Poor children! this sort of thing is much too hard for you.' The excessive humanitarianism of the 'advanced' educational theory must be abandoned, and along with it the modern disparagement of purely intellectual attainments. Children must become intellectually efficient and in order to become intellectually efficient they must make efforts even if the making be painful, even if they have to make them under pressure from without. The idea that things are too difficult is radically mischievous" (Huxley, 1930 quoted in the *Journal of Education 1931*: 59).

Moderate teachers searched for a compromise. They tried to retain the advantages of immediacy and interest that were associated with problem solving and at the same time gain the benefits of learning the concepts in a fairly direct way. For example, Westaway (1929) wanted to use a problem as a way of creating interest when introducing a new topic. Then he would present more formal lessons. But he stressed that there should be no pretence that the students are learning the real concepts of science while solving problems; it is simply a way of initiating interest.

In 1933 the *Journal of Education* printed the remarks of a British educator, Sir John Adams under the title *A Briton looks at American Education*. He gave an entertaining comparison of the British and American approaches. The British prefer a more rigorous education, with none of the "new-fangled" subjects. He calls this approach the "the good old grind" and those who support it the "good old grinders" (Adams, 1933: 48). The opposing American view is that all learning should be joyous. Students should always have a good time. He calls individuals who favour the latter approach the "primrose-pathers". Each approach goes too far, and a compromise is possible that includes both thoroughness and interest. While the English teachers are searching for this compromise, the Americans generally are not "yearning for" greater thoroughness.

> "The fact is that the Americans think that there is enough thoroughness in their system as it stands and they are repelled by the fear of pedantry and unnecessary dullness. It would be well if they could accept the assurance that there is no danger of American education becoming dull but there is a real danger of American education becoming superficial" (Adams, 1933: 48).

Ironically, at the time projects were becoming more popular, laboratory classes, introduced into all schools by scientists, were being eliminated. General science courses did not have laboratories and many science education specialists argued that it was more efficient to demonstrate experiments to students than have students carry them out themselves (Hoff, 1947).

The curriculum used in the 1930s contained elements from both the social efficiency and child-centred approaches and the single term "progressive" was used for both (Kliebard, 1986). Programmed instruction was introduced to make instruction more individual, but it was only individualized in the sense that children worked at their own pace on assigned material, not that children were able to express their own individuality. Kliebard (1986) points out that the term individuality had different meanings to different people. To child-centred educators, it meant building the curriculum around the individual child's creative interests; but to the social efficiency movement, it meant adapting the pace of instruction to individual learning capacities or even to streaming children according to their intelligence.

The life adjustment curriculum, popular in America in the 1940s, included courses in dating, marriage, child rearing, work experience and vocations. It was based on the social efficiency movement in that the curriculum was practical, and on the child-centred approach in that students were taught what interested them most. *The Forty sixth Yearbook of the National Society for the Study of Education*, stated that the subject centred approach was no longer accepted and there was no point in teaching concepts unless they were related to real life (Henry, 1947). To Hoff, a supporter of the progressive movement, it seemed as though the progressive movement would go on forever:

> "As evidence accumulates showing that the content of secondary subjects bears little relationship to success in college and as organizations representing the welfare of youth increasingly demand freedom from college domination, the

secondary school will be freed to minister to the needs of American adolescence. In the area of science teaching this will mean more functional programs. The present specialized science subjects of chemistry and physics will be replaced by generalized science courses stressing the practical phases which are functional in daily living" (Hoff, 1947: 14-15).

Progressive education in Nova Scotia

By 1911 students at the Teacher's College in Truro were learning about the social efficiency movement and were questioned about it on examinations (*Journal of Education, 1911*: 82). Similarly, programs in agriculture, mechanics and home economics, all indicating the social efficiency influence, began as early as 1907, and by 1932 technical schools had been built all over North America except in Nova Scotia and Prince Edward Island (*Journal of Education, 1932:* 130). Junior high schools were introduced in the USA in 1920, and in Nova Scotia in 1930. The committee formed to look at curriculum revision in Nova Scotia in 1930 consisted mainly of teachers rather than university professors. Of the ten members on the committee for natural science, one was a university professor, four were school teachers, four were supervisors of schools, and one taught at the Provincial Normal College. A general science course for grades 8 and 9 organized around practical subjects was introduced in Nova Scotia in 1932. In 1934 a biology course following a similar pattern was introduced in grade 10. By 1932, the progressive approach could be seen in textbooks and curricula of Nova Scotia.

The aims of the high school science curriculum in Nova Scotia published in the *Journal of Education* in 1932 were:

"1. To give students an idea of the importance and significance of science in all aspects of life.

2. To give information of definite service to home and daily life.

3. To develop specific interests, habits and abilities through the study of different branches of science.

4. To secure an element of continuity by knitting together previous science work through recall and through presentation of principles--new ones and elaboration of old ones.

5. To help the student discover whether he has an aptitude for the work and induce him to continue." (*Journal of Education, 1932*: 48).

This was expressed in more casual words as:

"An appreciation and respect for the services of science to industry. Citizenship through rendering an appreciation of science in advancing the welfare of society. The excitement of activities relating to better ideals connected to modern life. Development of specific values, interests, habits and attitudes and abilities. The pupil's discovery of his own aptitudes." (*Journal of Education, 1932*: 48).

Progressive approach in textbooks. College textbooks were used in grade 12 in Nova Scotia until 1965. These books were written by biologists and were not influenced much by the progressive approach. The text used by grade 12 students in Nova Scotia from

1944 to 1965 was *Foundations of Biology*, by L. Woodruff and G. Baitsell. It was a typical college text.

However, all textbooks produced after 1932 for grade 10 students were written by high school teachers or experts in science education, rather than scientists. How do these books differ from those written by scientists, and how do they balance the subject of biology with the progressive trends in education? Books written by educators fall into certain categories. In one category are those that follow the same pattern as used by scientists, but are out of date. Another category follows the pattern suggested by educators, and emphasizes the practical applications of biology rather than biology as a discipline. However, there were some good textbooks that followed the discipline of biology, and at the same time satisfied the requirements of educators. Two of these were used in Nova Scotia.

High school texts organized around biology. Just because a textbook adopts a subject-centred approach, does not mean that it presents the subject well. Two texts that were subject-centred, but were decades out of date, are: *Zoology For High Schools*, published in 1928 by J.F Calvert and J.H. Cameron, and *Botany For High Schools*, published in 1936 by A. Cosens and T.J. Ivey. Both books were authorized by the Minister of Education for Ontario, and their authors were Ontario high school teachers.

Zoology For High Schools uses the same organization as the book *Zoology* written by B. Colton twenty-five years earlier. Both texts begin with a description of arthropods, using the grasshopper as a representative insect. Then they look at other insects, other arthropods and finally, other animals: worms, molluscs and vertebrates. These texts cover only morphology and natural history. They are so similar that, in 1928, Calvert and Cameron appear to have used Colton's nineteenth century text as their model. They do not mention evolution and genetics even though both subjects were well understood by 1928. Similarly, the text, *Botany For High Schools*, written by Cosens and Ivey in 1936, is much less modern than the text, *Beginners' Botany* written by L.H. Bailey in 1908. It contains less information about photosynthesis, describes plants as they would have been described decades earlier, and does not even mention genetics.

Although the texts by Calvert and Cameron and by Cosens and Ivey used the discipline-oriented approach, they presented neither a subject matter that was up to date, nor the approach to biology that was common among scientists at that time. Some university professors also wrote textbooks that were out of date and unexciting. The good texts written by Bessey (1896), Bergen and Davis (1906) and Bailey (1908) were popular throughout North America so they were, no doubt, the *best* texts written at that time. The best texts were filled with enthusiasm and detailed understanding of biology. They allowed students to understand what science was, not by telling them, but in their choice of detail.

High school texts in the progressive style *Biology and Human Welfare*, written by J.E. Peabody and A.E. Hunt in 1930 was used in Manitoba as well as in the U.S.A. It was organized around practical themes rather than around biological concepts, so its approach was closest to the social efficiency ideal. The other text, *Biology in Daily Life* by F. D. Curtis and J. Urban, was written in 1949 and had more of a child centred approach. Both texts were popular in the USA

The authors of *Biology and Human Welfare* (1930) were educators who wrote a number of textbooks for high schools between 1912 and 1930 Some chapter titles are "Of what foods are made," "How plants manufacture food," "How living organisms are constructed," "What we should eat and why," "How drugs and beverages affect us," "How foods are prepared for distribution and used in living things," "Plants and organisms in relation to human welfare, and "How microscopic organisms are related to health and disease." Social problems like health and disease, use of plants in human welfare and diseases of crops occupy 29% of the book. A further 26% deals directly with human biology. The rest of the book (45%) deals with biology, but it would be hard for students to develop any coherent image of biology from this text It does not mention evolution, cell biology or genetics.

We might expect the chapter "How Plants are Related to Human Welfare" to describe plant breeding (described so effectively in 1908 by Bailey, and by other authors), but neither plant breeding nor genetics is mentioned. Instead there is a superficial early history of many crop plants. The following example shows how the authors have made an exciting field of biology into a tedious recitation:

> "**Cereal foods.** These foods include wheat, corn, oats, barley, rice and others. All these belong to the *grass family*, which includes more species than any other botanical group. The stems and leaves of these plants and of other grasses, when dried as *hay*, form a great part of the winter supply of food for plant-eating

(*herbivorous*) domestic animals. To man these cereal crops are most important, because of the valuable *grains* (fruits with a single seed) that develop from flower clusters at the top or along the sides of the stems (Fig. 139). These grains furnish generous supplies of starch and to a lesser extent proteins, fats. and mineral matter. When they are dried and ground, they form flours or meals of various kinds, which with the possible exception of corn meal, may be kept indefinitely if kept dry. These grain crops have been cultivated so long by man that scientists are not certain from what wild ancestor among the grasses any one of them has sprung. Wheat, for example, has been found in the pyramids of Egypt; it must have been put there more than 3000 years before Christ. Many believe that it was first grown by man in Western Asia in the region of Mesopotamia. Barley and rice are of ancient origin; but oats and rye seem to have been domesticated more recently" (Peabody and Hunt, 1930: 265-266).

Biology in Daily Life by Francis Curtis and John Urban was published in 1949, near the end of the progressive era. The authors were professors of education and members of the influential committee that wrote the Forty-sixth Yearbook of The National Society for the Study of Education. This textbook is particularly interesting because it represents a turning point in biology teaching. It was used extensively in American schools, so it reflects the teaching aims of the experts in science education in 1949. It could be said to represent the culmination of the ideals of the child-centred and, to a lesser degree, the social efficiency approaches to education. However, it also includes some features, like an emphasis on scientific method, that were just beginning.

This approach to scientific method was not typical of the ressive era but it was a cornerstone of the BSCS (Biological Sciences Curriculum Study) reforms in 1960 and has increased since. *Biology in Daily Life* has some features that represent the end of an era, and other features that predict the future.

Some chapters in the text teach biology, and others focus on the social applications of biology. For example unit two on "Using our resources wisely" discusses various aspects of conservation but gives no principles of biology. Unit three, "The world's food supply," quickly describes some plants then explains farming practices. Unit four, "Food and life," contains an introduction to the components of food and nutrition, and a description of human digestion, circulation, respiration and excretion systems. Unit five, "The conquest of disease," discusses health. About 44.4% of the textbook covers subjects that are closer to health and agriculture than to biology and 55.6% covers biology.

The authors explain the theory of natural selection in a fairly standard way while pretending at the same time, that there is no such theory, and while avoiding the word "evolution". They begin by saying.

> "No entirely satisfactory theory to explain how plants and animal forms change has yet been suggested. Moreover, what the exact nature is of the 'sorting process' that allows certain kinds of animals and plants to live in a locality and causes others to die there is not yet certainly known" (Curtis and Urban, 1949: 473).

This statement was probably made for the creationists. However, the authors then give a fairly good summary of Darwin's theory of natural selection.

They also explain genetics in a standard way, describing the experiments and laws of Mendel, relating genes to chromosomes and explaining incomplete dominance, sex-linked characters and the Rh factor in blood. They describe plant and animal breeding well, partly because they give specific details about crops like corn. They also mention eugenics in a restrained and responsible manner.

The book contains some serious errors: the description of meiosis is both confusing and wrong. The section on DeVries' theory of mutations (discredited 40 years earlier) is badly out of date.

> "DeVries continued his study of mutations for nearly ten years. During that time he raised at least fifty thousand evening-primrose plants. Finally, in about the year 1900, he announced his theory of mutations. According to this theory, plants and animals change, not slowly, over long periods of time, but at once. Thus new species are produced in a single generation.... This theory was accepted by scientists as a valuable addition to earlier ones that attempted to account for changes in plant and animal forms through long series of slight changes" (Curtis and Urban, 1949: 471).

Except for these errors the sections on evolution and heredity are well-written, and give an emphasis to biology that is consistent with the approach of scientists in 1949. However, these are the only chapters in the book that do so. Genetics was covered extensively in textbooks by both scientists and educators, probably because both groups valued it. biologists as an important new branch of biology, educators as a topic that is relevant to the daily lives of the students. Most other topics in the text are organized around social applications, and biology is secondary.

Approach to the processes and attitudes of science. The authors aimed "to develop scientific attitudes and an understanding of the importance of the scientific method" (Curtis and Urban, 1949: v). This book stands at the beginning of an era that has lasted to the present when scientific method is emphasized and placed in opposition to subject matter. A chapter at the beginning of the book explains science and a section at the end of each chapter contains questions called "As scientists work and think".

Books used in grade 10 in Nova Scotia. *Elements of Biology For Canadian Schools* (used in grade 10 in Nova Scotia from 1934-1955), was written in 1932 by Meier, Meier and Chaisson, experts in education. It is a blend of the biologist's approach to biology (as seen in college texts) and the progressive approach (as seen in Curtis and Urban). It is organized around biology but includes many practical applications.

A reasonable proportion of the book uses the type approach with the same plants and animals that had been described for 50 years. There is no explanation of evolution, but genetics is covered superficially and plant and animal breeding are described well. An excellent section on conservation is closer to ecology than practical conservation, with an introduction to marine and freshwater environments. The introduction to the chemicals of life is unusually good. Experiments and physiology are stressed. Considering how early this book was written (1932) it has a remarkably up-to-date treatment of chemistry, physiology and ecology. Approximately 30% of the book covers social applications and 70% discusses biology.

By 1955 a general science course was introduced into grade 10 in Nova Scotia, and the text *Science in action, Book 2* by Wallis, Ozard and Lewis (1955) was used from 1955 to 1965. This book does not contain many pages on biology. However, the sections on biology are fairly detailed and adopt a subject-centred approach, almost as if these chapters had been lifted intact from a biology textbook.

Chapter 4

Science Education after 1950

High school curriculum reforms circa 1960

In the early 1950s public support moved away from progressive education toward traditional educational values. Popular books like *Educational Wastelands* by Arthur Bestor (1953) criticized progressive education as being anti-intellectual. A similar book written in Canada was called *So Little for the Mind, An indictment of Canadian Education* (Neatby, 1953). There was a general feeling that schools should strive for excellence. All high school sciences were reformed, physics in 1957 and biology and chemistry in 1960. All three reformed curricula included more detailed and difficult explanations of the subject and an inquiry approach to learning, and they left out the practical applications of science that had been typical of the progressive era.

The American group that reorganized the biology curriculum, Biological Sciences Curriculum Study (BSCS), had good financial support ($9,000,000) from the National Science Foundation (Hurd, 1969: 125). They produced a variety of teaching materials, three textbooks with associated laboratory exercises, a separate laboratory block program, materials for gifted students, written subjects for discussion called *Invitations to Enquiry* and a book of original research problems called *Biological Investigations for Secondary School Students* (Glass, 1964).

They had an interesting approach to curriculum development. Sixty nine high school teachers and university professors met for seven weeks during the summer of

1960 to write three separate textbooks. They were grouped into teams, and worked on three slightly different approaches to biology. Each college biologist was paired with a high school teacher; the scientist was expected to provide expertise on content, while the teacher would decide on the appropriate level and manner of presentation. Half of the writers worked on the textbooks and half on the preparation of laboratory exercises that were intended to be closely coordinated with the textbooks. As laboratory experiments were prepared, they were tested by a group of two high school teachers and twenty students. The three versions of the textbook were drafted in seven weeks, then they were used immediately (1960-1961) in schools in a preliminary trial. In the summer of 1961 a second writing session took place to make improvements (Glass, 1964).

The BSCS committee wanted to change both the subject matter and teaching methods in science classes. The "great biological themes," were to be covered: molecular biology, biochemistry, ecology, behavior and structure and function. In addition, the "essential character of scientific activity," was to be taught. The essential character of scientific activity was defined as "the nature of science, including the discovery of new evidence, the development of science through correction of error, and the synthesis of new concepts" (Glass, 1964: 97). The character of scientific activity could be taught by emphasizing the historical development of each subject, the changing nature of scientific knowledge, the human side of scientific investigation and scientific inquiry. The first three were presented in the textbooks, but inquiry could only be done in the laboratory because students could learn science only by discovering scientific concepts for themselves, the way scientists do.

> "To understand the nature of the scientific process, one must participate actively in it one must investigate some problem, the answer to which is unknown" (Glass, 1964: 106).

Not only must students engage in discovery but it must be legitimate discovery, in which the student learns things that even the teacher did not know

> "One must approach the frontier of existing knowledge and deal not merely with what is unknown to the student, but with what is likewise unknown to the teacher and to the scientists who have prepared the teaching program to everyone in fact" (Glass, 1964: 106)

The developers of BSCS produced three kinds of exercise to deal with inquiry Laboratory exercises similar to those found in traditional classes but with less background explanation and more leading questions, "Invitations to Lnquiry," a series of descriptions of experiments or situations in science that were designed to reveal important features of scientific methods and "laboratory blocks," a series of experiments in a particular subject (e.g., plant growth and development,, that were done over a six week period while other classes in biology were cancelled (Hurd, 1969). The laboratory block was similar to the project approach, but students worked together in a more structured manner (Glass, 1964).

The BSCS texts

The green version. *High School Biology*, edited by W.B Miller, C Leth (1963), has an ecological approach that is sophisticated and interesting. Plants, animals, organ systems and genetics are described at an appropriate level for grade 10 students but the chapter on biochemistry may be too difficult for grade 10. For example, the description of cell respiration includes molecular models of pyruvic acid, acetic acid, oxaloacetic acid, citric acid and glucose, as well as descriptions of ATP, the Krebs cycle, glycolysis, and fermentation.

Each topic is described in a rather tentative fashion to show how scientists would approach it. The historical, and other side issues included. are interesting but at times confusing. For example, during a description of Mendel's experiments it is normal to describe a cross with one or two genes to show the kinds of results Mendel obtained. Instead, this text includes a discussion of probabilities, and shows the results of seven sets of crosses in one large table, thus bombarding the reader with too many details at the same time. Similarly, when the concept relating genes to chromosomes is explained, two pages are used to give Sutton's reasoning as it was in 1902, and another half page to explain the meaning of proof. Only then is Sutton's evidence given. This kind of presentation is confusing for novices. It is hard enough to relate genes to chromosomes, without also trying to follow the details of a long historical story and an analysis of what proof means in science.

Despite these criticisms, this is an excellent textbook. It gives the real flavour of ecology and demonstrates how intriguing science can be. Interesting descriptions of fairly recent studies in ecology show how this subject was developing. These are not dramatic experiments that led to breakthroughs, but rather modest studies, described in a way that makes them sound real. This text is comparable to some of the texts written by scientists, and used earlier in Nova Scotia (e.g., by Bessy), in that it seems to have been written by people who knew ecology intimately and were able to give details that conveyed a real sense of that science.

The yellow version. *Biological Science. An Inquiry into life.* by J. A. Moore *et al.* (1963) emphasizes genetics and developmental biology. This text has the same structure as college textbooks and is about as difficult. The treatment of subjects is unbalanced with too much emphasis on new topics. For example, 44 pages are devoted to viruses and bacteria, but only 21 pages to diversity of animals. Biochemistry is presented at a difficult level, but genetics and molecular biology are not as hard. The authors make extensive use of the historical approach. History cannot be used effectively to teach all subjects. The experiments, reasoning and details must be simple enough to be followed easily. A complicated topic like cell respiration has too much detail and background for a historical presentation but the authors try to present it historically. They describe the early chemistry of Priestly and give a detailed description of the discovery of oxygen and the Law of conservation of mass, a description of Dalton and the development of atomic theory, and an explanation of the beginning of biochemistry. Then they move quickly to a modern explanation of cell respiration, leaving out all the history between. If this gives students a better understanding of how scientists operate, it is an understanding of science as it was done a century ago, not today.

The authors of the BSCS green version managed to avoid this pitfall by describing fewer old experiments and instead, describing experiments that may seem more mundane but are recent. They try to accomplish less by describing less all-encompassing experiments but they do a better job at showing students what science is like because the events they describe are both more modern and more representative of real science. There are certain areas where a historical development of the subject assists understanding, and these should be selected. The method should not be used randomly.

The blue version. *Biological Science. Molecules to Man, Third Edition*, by C.A. Welch *et al.* (1973) emphasizes biochemical and physiological biology and the nature of scientific inquiry. It seems to contain two separate books meant for two different age levels. The first few chapters on science and ecology are written for grade 10 students, but emphasize socially important issues as much as biology. The next chapters present disjointed explanations of biochemistry and molecular biology that are too difficult for grade 10 students.

The first chapter, "Science as Inquiry" presents science as a subject, just as evolution and genetics are subjects. A series of examples of scientific problems are described, including one long example about Priestly's experiments with phlogiston. Science is less interesting as a subject than are digestion or genetics that it replaces. Examples taken from a variety of topics demonstrate scientific method, but each example is filled with confusing details, so it is hard to keep track of the theme. This chapter also gives the impression that scientists can make important discoveries by bouncing from one problem to the next, using scientific methods in the absence of background knowledge. But, scien : problems, removed from their context, no longer have any real meaning.

The section on chemistry, biochemistry, and molecular biology is disjointed and difficult to understand; e g , the chapter on energy contains an unnecessary comparison of straight chain and ring models of glucose. The chapter on photosynthesis contains a complicated description of the early history of photosynthesis, beginning with the work of Joseph Priestly. This is followed by an equally complicated and apparently unrelated description of the chemistry of photosynthesis. These lessons on biochemistry are too complex and depend on too much background chemistry for grade 10 students.

How successful were the reforms? By 1970, BSCS texts were used by 43% of the students in the U.S.A (DeBoer, 1991). The green version was most successful and was used in Nova Scotia from 1966 to 1990, initially for all academic grade 10 courses, but soon only for honours courses. The laboratory block program was used in honours grade 12 for many years. However, the program had many faults (Ausubel, 1969). Chapters on biochemistry and molecular biology in all three texts were too difficult for grade 10 students. The blue and yellow versions are poorly written; they lack coherence, and topics are not presented in a logical manner. This is not surprising considering that they were written in seven weeks by several groups of people, writing different parts of the text concurrently.

Descriptions of the curriculum reforms give the impression that without BSCS, the biology curriculum would not have been modernized around the new themes in biology (Glass, 1964; Hurd, 1969; DeBoer, 1991), but modernization was inevitable in the 1960s, with or without BSCS.

It is also sometimes said that the curriculum reform movement was led by scientists rather than experts in science education:

> "For the most part the curriculum reform movement was led by college professors with the help of school teachers. Education faculty played a secondary role if they were involved at all" (DeBoer, 1991: 158)

However, although scientists supported reform and helped write the new textbooks, the most important features of BSCS were determined by experts in education, not scientists.

The only real changes in the reforms were the short-lived reversion to teaching more difficult subject matter and the omission of practical applications of science. BSCS is most notable for teaching the structure of the discipline (or the essential character of science), and using inquiry learning, and emphasis on these features was evident in the literature and practices of science education before the reform period of 1960 (in the Forty-sixth Yearbook of Education [1947] and the textbook by Curtis and Urban [1949], for example). The developers of BSCS simply carried them further.

The Modern Period (1970-1995)

The rigorous subject content lost popularity quickly, and even those like Schwab, who helped develop it ten years earlier, were speaking out against it by 1970 (Tanner and Tanner, 1980: 59). However, inquiry learning remained popular until the 1980s. It was held up as an ideal even though it was difficult to accomplish in reality. Researchers in education conducted many studies to show that inquiry learning was more effective than traditional learning but their results were not conclusive. By the late 1980s science educators no longer supported inquiry learning; it was replaced by STS and constructivist teaching methods.

Scientific literacy and the rise of STS

In each period there are important social or practical applications of biology. In the late nineteenth century, these were in agriculture and health; during the first half of the twentieth century, the issues were plant and animal breeding and eugenics; today, we hear about pollution, destruction of habitat, genetic engineering and overfishing. The way these subjects were handled also changed.

In the nineteenth century, agriculture and physiology (hygiene) were essential subjects. They were taught in the schools in independent courses, as health is taught today. Agriculture was important because children who grew up on farms were obliged to spend most of the day in school so there was a fear that these children would lose both interest and ability in farming (*Journal of Education, April 1899:* 81). Agriculture was taught as a science subject in grade 10, and it was organized around agriculture rather than around the science disciplines. C.C. James, the author of the textbook used in agriculture classes from 1899 to 1910 (and also the deputy minister of agriculture for Ontario), included topics like: soil, crops, insects, diseases of plants, live stock, forestry and roads (James, 1899).

Courses in agriculture and physiology were the nineteenth century precursors to the general science courses taught during the progressive era (1920-1959). After 1920 curricula were modified to eliminate separate courses in agriculture and integrate such subjects into science courses. Some of these progressive courses were organized around social issues rather than science (e.g., Peabody and Hunt, 1930; Curtis and Urban, 1949). The progressive approach was very practical, giving a narrow preparation for life, and organizing curricula around subjects like health and hygiene.

Practical applications of science were dropped from the curriculum in 1960, but by 1970 a new movement, science, technology and society (STS) had developed to bring them back. This new movement differed from progressive education; it had a different outlook, and a different image of the curriculum. In the 1960s and 1970s people were discontented about the Vietnam war, and the decisions made by individuals in power. STS advocates wanted to organize the curriculum, not around the practical application of knowledge, but around socially important issues like environmental problems, overpopulation, pollution and energy shortages. The term, "scientific literacy" was used to describe this aim and a scientifically literate person was described as one who:

> "Uses science concepts, process skills, and values in making everyday decisions as he interacts with other people and with his environment and understands the interrelationships between science, technology and other facets of society, including social and economic development" (National Science Teachers Association, 1971, Quoted in DeBoer, 1991: 177).

The term "science-technology-society (STS)" was adopted for the teaching method used to develop scientific literacy.

The STS theme was discussed throughout the 1970s. By the early 1980s many teachers would add a discussion about the social implications of the topic at the end of each unit in biology. By the mid-1980s it was argued that the science curriculum should be organized around social issues, rather than around science itself, but this was resisted by many teachers who wanted to keep the disciplinary-based approach.

By 1990 the image of biology education had changed. Biology classes were expected to be value-oriented, discuss societal and environmental concerns and show science as a human activity. There was a common strategy for teaching students about values issues: "present the students with the dilemma, give them rational processes for thinking through the dilemma, but do not try to impose your own values on them" (DeBoer, 1991: 181).

The STS approach is now used extensively in North America, and since 1990 it has been used in Nova Scotia. Texts using this approach teach less disciplinary biology than other texts. Table 4 shows how much biology and how much applied knowledge is contained in these kinds of textbooks.

Biology textbooks written for high school students followed the same pattern as those written for universities during each period with the exception that during the progressive period (1910-1960) a greater percentage of the text was devoted to practical applications in grade 10 and the least attention to practical applications was given in university textbooks (see Figure 3). The high percentage for grade 10 represents the influence of books organized around practical applications.

Table 4. Content of some high school textbooks written from a social perspective

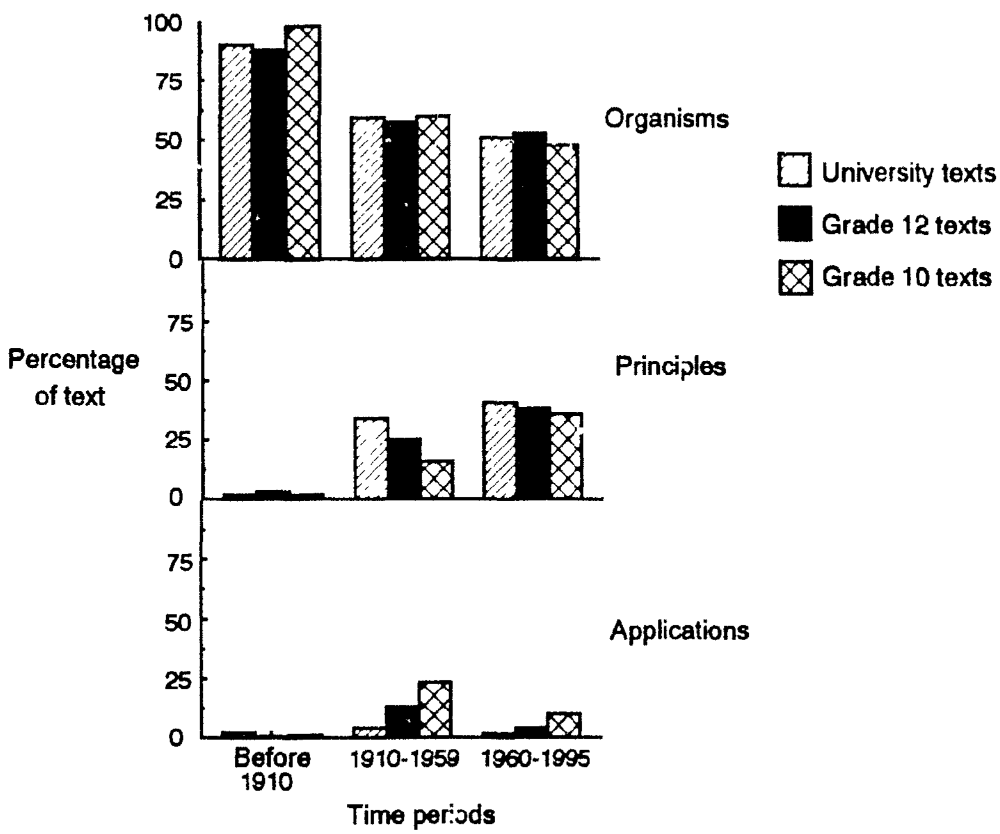
Year	Author	Title	Proportion of text	
			Biology	Applications
1863	MacAdam	*Chemistry of Common Things*	50	50
1901	James	*Agriculture*	31	69
1909	Brittain	*Elementary Agriculture and Nature Study*	40	60
1930	Peabody and Hunt	*Biology and Human Welfare*	45	55
1949	Curtis and Urban	*Biology in Daily Life*	56	44
1991	Aikenhead	*LoRST*	35	65

Constructivist approach

The constructivist approach to learning and teaching, developed since 1980, has rejected inquiry learning but stresses many of its features, notably the importance of teaching scientific methods and attitudes, the use of history to demonstrate how science progresses, the emphasis on the student, and the importance of allowing students to make their own decisions about their learning. It is compatible with STS.

Constructivist models of learning and teaching were developed by learning theorists to explain student misconceptions in science. Learning is seen as an active process in which a student constructs his or her own models of the world. New learning occurs as an interaction between new situations and older knowledge. Each individual's model must be respected, so this is a relativist approach. Teaching methods have been developed for this model of learning. This approach is popular and is recommended, for example, in *Project 2061, Science for All Americans* by the American Association for the Advancement of Science (1989), but it is too early to say how the constructivist method of teaching will fare in the long run.

Figure 3. Proportions of biology textbooks devoted to biology at the levels of the organism, principles and applications. Textbooks written for universities, grade 12 and grade 10 are compared over the major periods: the period of university influence before 1910, the progressive period (1910-1960) and the modern period (1960-1995).



Biology education in Nova Scotia in the 1990s

Grade 12 textbooks. The textbooks that have been used for grade 12 in Nova Scotia since 1966 are discipline-oriented. *Modern Biology* by J.H. Otto and A. Towle (1965, 1969, and 1982), was a popular text throughout North America and was used from 1966 to 1990 in Nova Scotia. The current textbook is *Biology, The study of life* Third Edition, by W. D. Schraer and H. J. Stoltze (1990). Both texts use the same organization as college texts but are smaller and simpler. There has been a gradual reduction in the diversity of organisms and an increase in biochemistry, molecular biology, behavior and ecology. In that it is basically subject-centred but sensitive to students, the approach to teaching biology in these texts is essentially the same as the approach used in grade 12 since biology was first taught in Nova Scotia.

Grade 12 curriculum. In contrast to the textbook, the biology curriculum has undergone a marked change in Nova Scotia since 1990. This change is reflected in the curriculum guide, written by educators and teachers for the Department of Education (Curriculum Guide No. 118, 1990, Biology 441, 541, Nova Scotia Department of Education). This guidebook presents the program that teachers are expected to follow.

The new grade 12 curriculum follows the STS approach. The focus of the biology program is "Survival in the environment" so only subjects like genetics and homeostasis are included (Curriculum Guide, 118, 1990: 6). The authors of the guide explain that they want to cover these topics in more depth and allow students to "reflect on the processes by which biological knowledge is constructed" (Curriculum Guide, 118, 1990: 6). Therefore they are reducing the content of biology and the variety of topics. Genetics, molecular biology, evolution, biochemistry (energy relationships like photosynthesis and cell respiration) and certain physiological functions related to regulation and control are still taught. There are also optional units on behavior, toxicology and pharmacology and careers in science. The subjects normally taught in grade 12 biology that are left out of the new course are: cell structure and function, physiological functions like digestion, transport, support and locomotion, plant structure and function, and diversity of organisms. Even when physiological processes like excretion or respiration are taught, only the principles are presented, not details of structure and function nor a comparison of the same processes in different organisms.

Less biology is taught. It has been replaced by a study of processes, technology and social issues. The change is dramatic; approximately one quarter to one half of the time is spent on process skills, technology, or social issues. The authors of the curriculum guide explain that they must emphasize content knowledge less and "information-processing skills" more (Curriculum guide, 1990: 52) because of the knowledge explosion.

The curriculum guide lists which biological concepts, technology or society connections, and skills or attitudes will be learned. Among the normal biology concepts learned (e.g., explore how DNA codes genetic information) are concepts that the authors call "*biological concepts.*" For example the following are among the biological concepts to be learned:

"Genetic research connects science concepts to social theory," "the role of Watson and Crick in DNA research,"

"Recognize the ethical nature of scientific research. Justify one's ethical perspective' (Curriculum Guide, 118, 1990: 81-87).

Among the technology or society connections to be learned are:

"the role of H.F. Wilkins and Rosalind Franklin in the discovery of DNA,"

"the role of politics on scientists and their research (Linus Pauling could not work in England with Crick and Watson in the 1950s because he was labelled a communist)," and

"the ethical issues inherent in genetic engineering such as technological evolution of humans or the creation of new life forms."

Some skills learned are:

"Conducting a literature search to research the life and contributions of geneticists such as Dr. D. Suzuki or Dr. K. Ogilvie (Acadia University),"

"identifying a minimum of three career possibilities if one studies genetics or becomes a genetic technologist,"

"critically evaluating the nature of experimentation, prediction and hypothesis in a research case (case study of Down's Syndrome),"

"critically analysing values associated with genetic screening (ethical decision making)"

This course marks a dramatic change in grade 12 biology, the biggest change since it was first taught in Nova Scotia. Less subject knowledge is taught and this is the first time grade 12 biology has been taken so far away from the approach of scientists and toward that of educators.

Grade 10 curriculum. The integrated grade 10 science program in Nova Scotia follows the STS method closely. About sixty percent of the year is spent on the unit called Science-Technology-Society which is based on the textbook, *LoRST, Logical Reasoning in Science and Technology* by Glenn Aikenhead (1991), so I will describe this text first.

The LoRST text tries to embed science in a social context. It organizes the course around drinking and driving. Students learn science subjects that are relevant for this topic, like concentration problems (in chemistry) that are needed in court cases on impaired driving and classification of mixtures that can be used to determine the composition of blood. This approach is intended to make science more interesting and meaningful because it develops a need to know. However, so much of the text is devoted to social issues that not much actual subject knowledge is taught. Only 35-40% of *LoRST* discusses actual science and technology subject matter; another 16% develops process skills. The rest of the book is devoted to the social issues and the kinds of reasoning that are normally associated with philosophy or law. Much of the book is devoted to explaining legal and scientific decision making, differentiating science from technology, defining logical argument etc. Some of these might be said to be *about science*, but they are not science.

Not only is the quantity of science reduced, but also the quality. The science is disjointed because each topic is mentioned only as it applies to alcohol or the breathalyser. For example, there is only enough about digestion and circulation to explain how alcohol gets into the blood and goes to the lungs. The digestive system below the stomach and duodenum is ignored because alcohol is absorbed across the stomach wall, and only the circulatory system between the heart and lungs is described. Similarly the only features of these systems mentioned at all are those associated with absorption and distribution of alcohol.

The science in LoRST is very simple (about grade 7 level). For example, the reader is expected to pretend he is a small submarine on a voyage through the blood stream. After entering the liver:

> "Your sub easily penetrates the cell membrane. The thin, jelly-like membrane is loose enough to allow some molecules to pass back and forth, but stiff enough to contain the large body of watery fluid--the cytoplasm--inside" (Aikenhead, 1991:204).

This over-simplified biology is mixed with extensive detail about alcohol and its effects on the body. We learn that the lining of the stomach produces mucus to protect the stomach wall from alcohol and students are put into the role of scientists when they are told that they will be able to judge surprising new evidence themselves (Aikenhead, 1991:203).

The LoRST book is the main resource used in the grade 10 integrated science program but not the only resource. The grade 10 program defined in the *Curriculum Guide, No. 136, 1993, Integrated Science 10,* published by the Nova Scotia Department of Education, lists the other topics studied as: a comparison of science with technology, toxic waste and independent study. There are some optional topics: agriculture and food science, space sciences, forestry/fisheries and marine science.

The concepts/student objectives for the Science-Technology-Society Topics 2 and 5, as listed in the curriculum guide, are:

"Topic 2: Science and Methods

Unifying Concepts: nature of science, energy, patterns of change, systems, modeis.

Concepts/Student Objectives

Science is a process of asking questions and seeking answers to better understanding the world about us. The scientific process employs a variety of methodologies.

1. Identify hypothesis, prediction, database, verification.

2. Become familiar with some of the principles associated with scientific research.

3. Describe the experimental procedure, outline the experimental results and evaluate hypotheses based on data, when given a scientific case study.

Technology uses a cycle of design and evaluation to solve practical problems.

1. Outline the technological cycle of design and evaluation.

2. Identify the technological problem-solving components when given a case study.

Scientific knowledge relies on reliable data and procedures.

1. Distinguish between reliability and accuracy.

Scientific knowledge can be used in making decisions.

1. Explain the general criteria for making legal, scientific and moral decisions.

2. Make rational decisions based on scientific data.

3. Determine the role of consensus-decision making.

The rules of logic and argument construction play a major role in the scientific decision-making process.

1. Appreciate the role of logic and values in critical thinking and decision making.

2. Apply the basic rules of logic and argument construction in decision making.

3. Critically analyse arguments by finding traditional fallacies in those arguments.

Heat is a source of energy which can be transferred.

1. Outline the process of heat transfer.

2. Quantify the process via calculation $Q=Cm\Delta T$.

3. Experimentally verify variables that affect the absorption or radiation of heat by an object.

Materials have different capacities for storing heat energy.

1. Explain specific heat capacity.

2. Give examples of how different materials have different specific heat capacities" (*Curriculum Guide, No 136, Integrated Science 10, 1993*: 101-104).

"**Topic 5:** Respiratory system and scientific models

Unifying Concepts: Systems, patterns of change, models

Concepts/Student Objectives

Breathing and respiration are different processes.

1. Make a diagram of body's breathing apparatus and label the main structures

2. Define respiration and provide examples.

3. Distinguish between breathing and respiration.

Volume of air per unit time is a function of homeostatic regulation by organism.

1. Determine the volume of air that an average student breathes under different circumstances.

(a) Calculate different types of breath volumes (tidal, deep breathing, vital volume, expiratory reserve volume).

(b) Construct a graph of volume of air and number of breaths.

(c) Use two graphs to determine the three types of breath volumes

Models are physical or intellectual constructs to make abstract ideas more concrete in nature and therefore easier to understand.

1. Suggest and evaluate different proposals for building a model by using creativity and intuition as well as empirical data.

2. Locate a science conceptual model and identify its advantages and disadvantages.

3. Propose and evaluate different designs for building a technological model" (*Curriculum Guide No 136, Integrated Science 10, 1993*: 112 113).

The language of science and of STS. The large vocabulary is one of the biggest problems in biology education. There are so many new words, but at least each word has only one meaning. STS eliminates much of the language of biology by talking of mini-subs etc., but STS designers have substituted a new more complex language instead. In STS we read about "models, problem solving strategies and design process." We are asked to "operationally differentiate between" and to "develop competency at discussing variables, accuracy, reliability, basic assumptions and scientific laws and theories" and to "make rational decisions based on scientific data" and to "differentiate between values associated with the public and private science" (Curriculum guide, 1993: 103-130). The words used in science have a well-defined meaning, while the language of STS is cumbersome and ambiguous. The section on biology in the text *LoRST*, does not contain many biological terms but instead it contains such words and phrases as "public policy," "miniaturized submarine," "London subway system map," "maximum BAC (blood alcohol concentration)," "All scientific knowledge is tentative," "How slippery are cell membranes?" and "Conviction overturned" (Aikenhead, 1991: 196-209).

Chapter 5

The Redefinition of Science by Science Educators

Science educators have gradually changed the emphasis in their definition of science from "a body of knowledge" to "a method of obtaining knowledge" and "an attitude or way of thinking". This redefinition took place too slowly to be apparent, but as a result of it, educators now have a totally different definition and image of science than do scientists, and a different philosophy for teaching it. Probably neither group really understands how different their views are. I will trace the development of this redefinition of science within education.

In education there is an overlap between what is considered curriculum and what is considered a teaching method. Originally curriculum was the body of knowledge to be taught and it was based on the discipline, e.g., biology. Members of the social efficiency movement wanted the curriculum to be based on what was useful and relevant for society rather than disciplinary knowledge. The child centred educators, on the other hand, wanted to teach what was interesting to students. This opened up the question "What body of knowledge should be taught and who should make the decision?"

Kilpatrick (1918) changed the definition of curriculum when he redefined project as almost any activity or problem that students plan purposefully and find interesting. He redefined subject matter in terms of the project. The subject matter was no longer the disciplinary knowledge to be learned; now children learned what emerged from their projects, and subject matter was just a tool to help them learn (Kliebard, 1986).

Before 1918, teaching method was distinct from the subject matter (curriculum) and was secondary to it, but Kilpatrick removed this distinction when he defined as curriculum, "the method used by students to learn" (solving problems or conducting projects). So the method of learning became the curriculum (what is learned) and the subject matter became a tool used in the process (part of the method).

Kilpatrick (1932) argued that we live in a rapidly changing world so subjects learned today may not prepare students for the changed world of tomorrow. Students must learn how to solve problems they will encounter in the future, and they can do this by using the problem solving processes today that they will use in the future. The most valuable part of education is the experiences of students as they solve problems. The subjects themselves lose their value as curriculum because they may go out of date. This reversal in priorities, making the experiences or method of learning more valuable than subject knowledge, has remained in education throughout the twentieth century.

Also important was Kilpatrick's definition of a project as any activity that a student carries out with some purpose in mind and with some degree of enthusiasm. He wanted to remove all coercion of the student. This condition has also remained in science education and has been important in the redefinition of science.

By the 1940s, the idea that the method or activity is more important than the subject knowledge had been applied by science educators to scientific method. Educators began to stress methods used by scientists during discovery rather than the methods used by students to learn in classrooms. In the *Forty-sixth Yearbook of the National Society for the Study of Education*, the committee talked about "scientific attitude" and "scientific methods" and stated that subject knowledge itself is secondary:

> "Since the logical development and mastery of the subject matter of biology is not of itself a primary goal, and since in any event the field is too broad to be covered adequately in the time provided in school, then it follows that considerable variation in topics covered and in the order of topics will be legitimate and desirable, as circumstances vary" (Henry, 1947: 184).

In 1949 Curtis and Urban echoed these ideas and tried to put them into practice in their high school textbook (described earlier). They say about the aims of their text.

> "One [aim] is to develop scientific attitudes ('As scientists think'), another is to develop an understanding of the importance of the scientific method, and facility in its use ('As scientists work'). These objectives are not attained to an appreciable extent incidentally or an inevitable concomitant of studying subject matter, but they can be substantially achieved only when materials specially designed to effect them are taught directly" (Curtis and Urban, 1949: v).

Not only was the priority changing from subject knowledge to scientific attitudes and methods, but the opinion was forming that attitudes and methods cannot be learned as part of the process of learning subject knowledge; they must be taught specifically. This placed attitudes and an understanding of scientific methods *in competition with* biological knowledge for teaching time.

Curtis and Urban explained science in a separate section, and they referred back to it continually throughout the book. There is also a section at the end of each chapter, called "As scientists work and think," with questions like the ones below:

"Read again pages 475-482 dealing with Mendel's experiments. Which scientific attitudes are shown in the account of Mendel's work? Which of the elements of scientific method are indicated?" (Curtis and Urban, 1949: 506).

and

"In 1865 Mendel presented the results of his research on pea plants before the Brunn Society of Natural history. To his intense disappointment, for he realized the significance of his results, nobody present displayed interest in his report. It was later published in the local scientific journal, but this journal had limited circulation and no prominence. Hence Mendel's research remained unnoticed until about fifteen years after his death. By 1900 however, each of three noted biologists, a German, a Hollander and an Australian, had come across the published paper. Impressed with its importance, they performed with plants experiments similar to those done by Mendel and secured the same results that Mendel had secured. Within another two years, other scientists carried out experiments of the same kind with animals. Their results were the same as those secured by the four scientists who had experimented with plants. The great honours that should have come to Mendel at least a third of a century earlier were then given to him posthumously. What scientific attitudes are related to this account?" (Curtis and Urban, 1949: 507).

Throughout the text the authors continually refer to the methods and attitudes of scientists. The authors treat scientific method as something unique, almost magical. This textbook, written in 1949 is particularly interesting because it is a direct precursor to the BSCS texts of the 1960s, with its preoccupation with scientific processes and attitudes at the expense of subject matter.

The major figures responsible for BSCS took a leap forward in redefining science explicitly. They also reintroduced inquiry learning and defined it as *the scientific method*. Kilpatrick had stressed that the methods of learning were more important than subject knowledge; science educators of the 1940s had moved the emphasis from methods used by students to learn, to methods used by scientists during research, and they concentrated on describing to students how scientists work; developers of BSCS in the 1960s moved the emphasis back to students by saying that students learn science in classrooms by using the *same* scientific methods that scientists use in discovery.

> "Intellectual activity is everywhere the same, whether at the frontier of knowledge or in the third grade classroom. The school boy learning physics *is* a physicist and it is easier for him to learn physics behaving like a physicist than doing something else" (Bruner 1960: 14).

Jerome Bruner, a psychologist who was influential during the curriculum reforms, favoured teaching the "structure of the discipline" (Bruner, 1969), but the term is ambiguous. Passmore cites two meanings for 'structure' of science: the leading ideas and conceptual system of science, or its logic, methods of explanation and types of theory (Passmore 1980: 97). To BSCS organizers, "structure of the discipline" did not mean a discipline-centred curriculum or the structure of *knowledge*, but rather "the way biologists think and work." Therefore students were to learn the structure of the discipline, not by learning the subject matter, but by behaving like biologists and carrying out experiments, and by learning how scientists think. Bruner suggested that a subject-centred approach that concentrated on biological knowledge was teaching just the *conclusions* of the scientists without providing a sense of the scientists' spirit of discovery, and this practice produced knowledge unrelated to the essence of the subject (Bruner, 1960; DeBoer, 1991). On the other hand, if students understood the structure of the discipline--the way scientists tackle problems--they would then be able to transfer that understanding to new problems and issues.

Joseph Schwab, a curriculum specialist, associated with BSCS, who reintroduced the idea of inquiry learning questioned the truth of knowledge, even up-to-date knowledge. A concept (or construction in the mind) comes first, before the facts are known, and guides the scientist in what experiments to do. This means that the facts learned do not represent the ultimate truth, but only a selected view of the world, formed by the scientist who decided what facts to search for and how to interpret those facts. Students should be taught that science is not a body of literal and irrevocable truths but an investigation of some aspect of knowledge. Scientific knowledge is fragile and subject to change. Old knowledge is replaced by new, and since there are so many scientists, the rate of change is high, and students will have to learn completely new knowledge several times in their lifetimes, every 5 to 15 years (Schwab, 1962: 199).

Schwab argued that since scientists no longer viewed scientific knowledge as stable truths to be discovered and verified, but as "principles of enquiry--conceptual structures--which could be revised when necessary," school science teaching should also promote this revised notion of science. Science textbooks therefore should present not merely the conclusions of science but also the factual and theoretical evidence that supports these theories (Schwab, 1969).

Glass added to this by saying that knowledge in science is constantly going out of date because of the "extraordinary increase in scientific knowledge in our century" (Glass, 1970: 23).

> "By the end of this century the fund of biological knowledge will have redoubled seven, or even ten times the amount to definitely more than one hundred times, and perhaps even more than one thousand times, what it was in 1900" (Glass, 1970: 24).

The BSCS committee said that it did not really matter *what content* was taught because the methods of science were more important.

> "It is not necessary that the average man be acquainted with the latest theory of science but it is necessary that he should understand as clearly as possible the purpose and methods of science. We were agreed that the boy or girl in school cannot comprehend the nature of science by learning facts about nature. Instead, real participation in scientific inquiry, and as full a participation as possible, should be provided. Only by engaging in the steps of scientific inquiry may a student become able to discern the true difference between sound experiment that provides evidence and complex instrumentation that offers a show between evidence and authority, between science and magic. This conclusion called for a thorough and radical change in the character and emphasis of most current science teaching" (Glass, 1964: 97-98).

In conclusion, Bruner, Schwab, Glass and other organizers of BSCS discounted scientific knowledge by saying that scientific knowledge goes out of date too quickly to be valuable and that scientific knowledge is relative or tentative so it need not be taken too seriously by students. Even more seriously, they removed scientific knowledge from active science by calling it the "conclusions" or "products" of science. They created a dichotomy, with scientific knowledge on one side--as just the past products of science, tentative, not to be believed as true, likely to soon go out of date, nothing but dry information On the other side was science itself--the activities and ways of thinking, the methods by which new things were developed. It is not surprising that teachers did not want to teach scientific knowledge when scientific methods and attitudes seemed to be much more valuable and exciting, and much more central to science itself.

Students could learn the processes of scientific inquiry in two ways: one was to learn about the history of scientific discoveries and the other was to learn *by* discovery, with the same experimental methods used by scientists.

Recently, inquiry methods have become less popular and STS and constructivist methods have replaced them. These teaching methods are also open-ended. The constructivist approach retains the relativist approach to science and the idea of student control, but it changes the method by which students can learn. Students will still learn science the way scientists learned it, but the discovery stage is not emphasized; instead the decision-making phase of science, in which scientists decide which theory to accept, is given priority. It is assumed that if students go through the process of making decisions as scientists do, they will come to the same conclusions as scientists.

When people learn by discovering for themselves, or analyzing and making their own decisions about what theory to accept, the results will be open ended; they can't be defined by someone else. However, science educators expect students to learn the same theories and concepts with inquiry or constructivist methods that scientists have earlier discovered. It is impossible to guarantee closed-ended results from an open-ended process, and this more than anything else makes these open-ended methods impractical

The new emphasis on the methods and attitudes of scientists at the expense of scientific knowledge does not appear just in the literature of science education, it is being implemented in schools in Nova Scotia. The educators who now control the biology curriculum of Nova Scotia have reduced the amount of subject knowledge taught and replaced it with an analysis of scientific methods and scientific attitudes.

The changing definition of science and devaluing of scientific knowledge originated in the community of educators. Neither scientists nor educators probably appreciate the large gap that now exists between the definition of science used by science educators and the definition used by scientists. Individual statements made about science by members of the two groups may not seem so different, but when all the statements are added together, the image of science supported within education seems to be dramatically different from the view scientists hold.

SECTION 2

STUDYING SCIENCE

Since 1930, there has been an increasing emphasis on teaching the methods and attitudes of science instead of the subjects of science. But it is not clear what those methods and attitudes are. The supporters of different teaching methods have definitions of science that differ from each other, but also from those held by many scientists.

In this section I will summarize recent research on science. The definition of science is in a state of flux. Since 1960, many groups have studied it and created different images of it. I will use examples from a specific scientific episode, the discovery of penicillin, to illustrate the discussion of science and teaching methods. The development of penicillin provides a good example because it is interesting as science, but not too complex, and it has been used extensively in science textbooks to illustrate how science is done. After summarizing the story of penicillin, I will give examples of its use in school science.

Chapter 6.

Survey of Recent Work on Science

In the last thirty years, there has been active debate about the nature of scientific knowledge and the methods used by scientists to create it. A variety of specialists have taken part; philosophers, historians, sociologists and psychologists, but scientists have contributed only marginally to these discussions. Science is a diverse and complex subject, and it has been studied in a variety of ways. Each study captures a particular feature of science, but the composite view is more interesting and valid than any of the isolated images. Some theories about science appear to contradict each other, but they are not as incompatible as they seem. Each theory contains an element of the truth, and only becomes untrue when it pretends to represent *all of science* rather than just one aspect of it. Scientific methods are not uniform, either in time or place. Each new concept goes through many stages as it is developed; it continues to play a role in active science, even after it is accepted by members of the scientific community, as it is integrated into a larger framework of theory. I will try to build a composite image of science that is relevant to science education.

Traditional views of science

Science attempts to explain nature by forming theories and making testable predictions. Before 1960 philosophers of science thought that scientists used two methods: one based on induction and the other on deduction. With the method of induction, the scientist makes observations and records results, then generalizes from these to form theories. On the other hand, the hypothetico-deductive theory (using deduction) describes science as a process with two steps. The first is the discovery of an idea or hypothesis and the second is the testing of the hypothesis. It is this second step that makes scientific knowledge dependable. The hypothetico-deductive theory of science was popular until the 1960s, and was supported by Karl Popper, an influential philosopher of science. However, Popper also supported the view of science as a process of solving problems (Hodge and Cantor, 1990; Nickles, 1990).

Traditionally the following assumptions were made about science: objects of the natural world are real and have an independent existence (Newton-Smith, 1989); scientific theories are true because they are arrived at by using evidence and logic--the correspondence theory of truth (Hesse, 1974); science consists of successive approximations toward the truth, and only one theory will remain acceptable once more evidence is collected (Hesse, 1980); a scientist is able to experiment and theorize about the world objectively (Brown, 1989); and science is cumulative--once a fact has been discovered it is added to other facts, and is never abandoned (Brown, 1989).

The transition period

The image of science began to change after 1950 as a number of new ideas were put forward. For example, Norwood Hanson proposed that observation is theory-laden (Hanson, 1961). This seemed to undermine science since, if it were true, two scientists could experience the same event but see it differently because they have different expectations (Hodge and Cantor, 1990: 847). This argument destroyed the link between evidence and truth that had seemed so strong, and suddenly scientific knowledge seemed to be relative just like other knowledge. The most dramatic new ideas were proposed by Thomas Kuhn in the book, *The Structure of Scientific Revolutions* in 1962 and 1970. Kuhn ignored traditional ideas of scientific method and described a completely different process. He popularized the term paradigm but gave it two distinct meanings. A paradigm was an exemplar, a problem solution that can be used as an example of how to solve a similar problem. Kuhn argued that scientists solve problems by using analogy -by seeing how current problems are similar to solved problems. On a larger scale Kuhn defined a paradigm as an umbrella of beliefs that all members of a community share He emphasized that the traditional idea that scientists argue over theories is wrong. Instead, scientists agree on a common general paradigm, and concentrate on solving the small problems associated with that paradigm.

He identified three stages that subject areas pass through. Prescience is found early in the development of a subject, before agreement has been reached on a basic paradigm. Once a common paradigm is accepted, scientists are able to operate in a different way and a new form of science, called normal science, develops. Then scientists solve small problems that do not question the prevailing paradigm. Occasionally revolutions occur, when results that can't be explained by the existing paradigm cause the community to reject it and adopt a new one. This revolution brings a new view of the world and a new set of problems. During this revolutionary period, competing theories are incommensurable and cannot be compared on strictly rational grounds; therefore the scientific community uses social factors as the basis for these decisions. Kuhn captured the flavour of the issue in his description of the revolutionary period

> "The proponents of competing paradigms practice their trades in different worlds. Therefore they see different things when looking from the same point in the same direction" (Kuhn 1970: 150).

His description of scientific revolution received enormous publicity, and was taken as evidence that scientific knowledge is relative, but Kuhn's revolutionary science has not been well accepted by scientists, and Kuhn has modified his own view of it recently (Kuhn, 1990, 1991).

On the other hand, Kuhn made three points about science that did not attract much attention but have important implications for science education:

1) First, the acceptance of a paradigm in normal science allows scientists to concentrate on small details, and this is what makes science so efficient and effective. Since individuals don't question the basic truth of the paradigm, they can concentrate on small problems. This seems unattractive to anybody outside science. However, progress results when this kind of consensus is formed.

2) Second, scientists don't learn science through theories, which they then apply to examples. Instead they learn theories by solving problems. This activity allows them to see analogies between situations, and gradually they begin to express this as a theory. Students learn science in the same way, by doing problems that are closely modeled on previous problems that they are able to solve (Kuhn, 1970: 47). It is not that students can form theory for themselves by doing problems, but that they will become

comfortable with theory by having practice in solving problems.

3) Finally he said that scientists continually rewrite the history of science, giving a false impression of what has happened in the past (Kuhn, 1970).

In 1975 Feyerabend, a philosopher with radical views about science, rejected almost all that traditional philosophers of science valued, including the idea that science is based on logic and evidence. He claimed that evidence cannot be trusted because it is theory-laden and favours older theories (Feyerabend, 1975). Feyerabend's ideas were echoed later by sociologists who were attracted to relativism. These new and fairly extreme ideas about science helped people clarify their understanding of science by providing an alternative view, but they have also added confusion for people who are not familiar with science.

New directions of science

Studies of science seemed to go off in several directions after 1962. Some used Kuhn's work as a starting point, and others started with the traditional image of science and modified it into a more flexible and realistic view of science.

Moderate sociologists and the social nature of knowledge

We may call those sociologists moderate (e.g., Bloor, 1983; Gilbert and Mulkay 1984; Barnes, 1990) who admit that logic and evidence are used in science, but believe that social factors like interests and goals also play a big part. They argue that factors, like the theory-ladenness of observation, the incommensurability of theories, and the underdetermination of theory by experience, all support the view that logic and evidence can't account for scientific knowledge. Therefore, knowledge is an interpretation of experience rather than a reflection of experience (Barnes, 1990: 69). This argument was also made by Schwab (1962), who reintroduced inquiry learning into science education during the curriculum reforms, when he said that scientific knowledge is tentative.

Radical sociologists and knowledge as construction

Another group of sociologists (e.g., Latour, 1987, Woolgar, 1989) want to show scientific knowledge as a social construct. They have used techniques from anthropology to study scientists. These sociologists work as laboratory assistants and record all they see. By maintaining their distance, they try to identify and explain the practices that scientists take for granted. This is really an attempt to carry out theory-free observation in order to develop an authentic picture of science (Woolgar, 1987).

They have been only partially successful. They have identified some interesting features of science that others missed, but they have seen only what is on the surface and have missed the underlying explanations. They are just as guilty of seeing from one point of view as those they criticize. Latour and Woolgar (1979) make the controversial claim that scientific knowledge is constructed rather than discovered. They argue that not only the theories but also the objects, like electrons and antibiotics, that scientists study are created by scientists and would not exist without scientific activity. Furthermore, scientists essentially fool themselves and others into believing that the objects they describe are real, and were waiting out there to be discovered. These sociologists have considerable influence with experts in science education, and their books are found on recommended reading lists for science teachers (Curriculum Guide, 136, Department of Education, Nova Scotia, 1993).

Feyerabend and the sociologists have challenged the validity of older images of science, but also, in some cases, the validity of science itself. Some of the sociologists believe that they have only destroyed the unrealistic view that was formerly held about scientific knowledge (Hacking, 1983), but others think that relativism has destroyed the faith of members of the general population in science itself (Laudan, 1990). Some of the newest science curricula adopt the viewpoints of radical sociologists, and risk developing an anti-science attitude among students.

Many new directions

Historians and sociologists have studied aspects of science not looked at earlier. For example, Gooding (1982, 1986, 1989a, 1989b) and other historians have described frontier science, the uncertain first stages of discovery; Hacking (1983) wrote of the importance of experiment; Gilbert and Mulkay (1984) concentrated on the scientific literature; Barnes (1985) analyzed the effect of community structure on scientific knowledge; Hesse (1974, 1980) discussed the overall structure of scientific knowledge; and Nickles (1988, 1990) described reconstruction as a process that occurs at all stages of science and must be understood if we are to understand how to teach science. Each of these scholars has clarified some feature of science and I will describe their work later.

The realists

There has been a gradual shift in the position of realists from the traditional view of science to a more moderate one, as these philosophers and scientists have responded to the relativist challenges. There has also been a slow change in the meaning of certain words relating to time and truth. Realists believe that there is a world, largely independent of us. that we can learn more about. However, they no longer accept the correspondence theory of truth, and they now argue that we cannot be *sure* that a theory is definitely true even when we think it is reasonable to believe in it (Hesse, 1974; Brown, 1989). Since scientists are humans and are influenced by a variety of factors, they can make decisions that are not entirely rational or based solely on evidence; social factors always play some role in scientific decisions (Brown, 1989). Therefore, scientists simply choose the best theory available at the time.

However, scientists themselves still generally believe that in the long run social factors will be filtered out and theories based on evidence and logic will emerge. They accept that we strive for truth in the future rather than expecting to be sure about it for the present. They always leave open the possibility that views may change in the future given new evidence, but at the same time, they accept current theories without hesitation on a practical level so that they can use them. This view of science is not being transmitted to students. Scientists have much more faith in the reality of their concepts at this practical level than do modern teachers and experts in education.

Chapter 7

The Story of Penicillin

I will use the discovery of penicillin, as an example of scientific research, to illustrate the discussions of science and science teaching that will follow. It provides a useful example because, as science, it is fairly normal and does not depend on complex scientific theory, but, as medicine, it is exciting, and, as a story, it is intriguing with some unexpected twists. But mainly, this is a good example because the story of penicillin demonstrates how easily science can be misrepresented in both the popular press and school textbooks. I will briefly tell this story starting with the incorrect account that was popular for twenty years, then continuing with an accurate historical account. Finally, I will show how this story has been told in some high school textbooks.

Popular accounts

Popular accounts written before 1965 tell how Fleming isolated penicillin in 1928, but had some difficulties in purifying it because chemists refused to give him the help he needed. Then penicillin was produced in large quantities during World War II, and it had an enormous impact on medicine. It was difficult to explain why penicillin was not used medically until 1940, twelve years after it had been discovered. Some reports said that Fleming had developed penicillin by himself against great odds. Others said that Fleming spent years trying to persuade others to take penicillin seriously. André

Maurois (Fleming's official biographer) wrote in 1959:

> "There is something deeply moving in the spectacle of this shy man with his burning faith in the capital importance of a piece of research trying, in vain, to persuade those who alone could have made its practical application possible, to see as he did" (Maurois, 1959: 154).

After the war Fleming was given many prizes and awards, including the Nobel Prize, for his discovery of penicillin. He was popular with the general public all over the world, even though he was not a great speaker, and did not have much charm. Gwyn Macfarlane (1979, 1984), a scientist who watched the development of penicillin and wrote two books on this subject, suggests that after the war people were tired of "dictators, military leaders and powerful personalities". They knew Fleming must be wonderful because he had given them penicillin and yet "they saw a simple, modest little man, [so] they went wild with gratitude" (Macfarlane, 1984: 259).

The real story

Fleming did not develop penicillin. He found it in 1928, extracted it from a culture of *Penicillium*, and worked on it for a short time. By 1931 he had abandoned it as an antiseptic for medical use and used it only as an ingredient in culture medium to selectively grow certain organisms. Penicillin was developed therapeutically in 1940 by a group of scientists at Oxford under the leadership of Howard Florey. However, when penicillin made such an impact on the world, Fleming managed to get the credit, and the group at Oxford were ignored by the public. Early accounts propagated the "myth" described above of the development of penicillin, but several scientists who knew what had happened later told the real story.

By 1928 Fleming had worked on antiseptics as a microbiologist in St Mary's Hospital in London for twenty years. During World War I he showed that prolonged application of antiseptics to wounds did more harm than good because it damaged white blood cells more than it hurt bacteria. In 1920 he discovered the enzyme lysozyme, which is found in many animal fluids such as tears and mucus. He had tried to culture some nasal mucus, but the Petri plate became contaminated with a bacteria. Fleming noticed an area immediately around the mucus where colonies of bacteria were being destroyed. He concluded that the mucus released a substance that diffused out and killed the bacteria, and he worked on the substance (lysozyme) for several years. Lysozyme kills bacteria, but only harmless bacteria, so it is not important medically. One of Fleming's normal laboratory techniques was to test the toxicity of an antiseptic (defined as any substance that would kill bacteria) on various bacterial species. He would add antiseptic to portions of media in a Petri plate and see how close colonies would grow to it.

In 1928 Fleming found the mold, *Penicillium* growing on a plate containing colonies of *Staphylococcus*. His discovery of penicillin repeats almost exactly, his earlier discovery of lysozyme. In each case he observed that a plate containing colonies of bacteria, along with a larger unit (mucus or *Penicillium*) had a zone around it free of colonies. He drew the same correct conclusions on both occasions--that a substance toxic to bacteria was being released by the mucus or mold. On both occasions he did the same thing; he extracted the active substance (lysozyme and penicillin) for further tests. Fleming's response to the discovery of penicillin was not unusual for a bacteriologist working on antiseptics. He was lucky because his strain of *Penicillium* produced unusually large quantities of penicillin, and the effect on surrounding bacteria was much more noticeable than normal (Hare, 1970).

After isolating penicillin, he tested its toxicity on white blood cells and bacteria. It did not damage animal cells, but it was toxic to disease-causing bacteria. He asked some students to purify it chemically so that he could try it on patients, but they were unsuccessful. He injected some penicillin into a healthy animal and found that it was not toxic. He also tried to apply it locally on an eye infection and some wounds, but with mixed success. Penicillin was frustrating to work with: it was unstable and hard to purify. It was also not clear, to those who worked on it, whether penicillin was effective against infections. There seemed to be no special reason to pursue it. Fleming (and all others who knew about it at that time) failed to take one important step--they did not inject penicillin into infected animals to see if it could cure disease. Therefore, they did not find out whether it would be effective medically. By 1931 he gave up on it as an antiseptic.

Fleming did continue to grow *Penicillium*, and added penicillin to culture medium when he wanted to grow *B. influenzae*, a bacterium that was difficult to grow in normal conditions. Penicillin did not harm *B. influenzae,* so Fleming used it to destroy competitors in the culture. The only papers he published about penicillin described how useful it was as an ingredient in culture media. One paper, written in 1929, was called:

"On the antibacterial action of cultures of a *Penicillium*, with special reference to their use in the isolation of *B. influenzae*" (Macfarlane, 1979). In this paper he mentioned that penicillin was not toxic to humans and might be added to bandages to combat local infections.

Background to the discovery of penicillin

Others, before Fleming, had noticed that some molds and bacteria produce substances that inhibit bacterial growth, and had collected and tried to use these substances therapeutically. A book, published in 1928, listed several hundred discoveries like Fleming's (Macfarlane, 1984: 136). Many of the discoverers had used the same methods that Fleming used to isolate the antibiotics and to treat human infections. For example, in 1871, Lister studied substances produced by a species of *Penicillium* and wrote to his brother: "Should a suitable case present, I shall endeavour to employ *Penicillium glaucum* and observe if the growth of the organisms be inhibited in the human tissues" (Lister, 1871, quoted by Macfarlane, 1984: 136). An antibiotic, called pyocyanase, was produced on a commercial scale by 1901 and used in Europe (Wainwright, 1990), but it gave inconsistent results and was abandoned.

In 1910 Paul Ehrlich looked for and found, what he called, a "magic bullet". He used a principle that he had seen at work in bacterial staining. Dyes had been found that could make bacteria visible in human tissue because they stain the bacteria preferentially. The stain attaches to a specific component of bacterial cell walls that is not present in animal tissues, so only the bacteria are stained. Ehrlich reasoned that if poison could be attached to such a dye, it would attack only bacteria--like a "magic bullet." He tried 606 compounds before he found salvarsan, a chemical that was effective against syphilis but also had some toxic effects on humans (Sheehan, 1982).

The 12 year gap. After the war, it seemed amazing that penicillin should have been discovered in 1928, but not developed for medicine until 1940. Apparently, Fleming complained in 1952 that he had demonstrated the effects of penicillin in 1936 to the Congress of Microbiology, but nobody paid any attention (Maurois, 1959). However, a colleague who worked closely with Fleming disagreed and said that Fleming was convinced that "there was very little future in the stuff" (Hare, 1970: 108). He can hardly be blamed for failing to appreciate penicillin's potential. In 1928 nobody was sure whether it would even be possible to find a chemotherapeutic agent that could kill bacterial cells while doing no harm to animal cells.

Two events occurred in the 1930s that changed the climate of opinion about antimicrobial substances. One was the discovery of sulphonamides, which influenced the philosophy of medical treatment. In 1932 Domagk, in Germany, found the first of the sulphonamide drugs. Suddenly, there was great interest in the possibilities of chemotherapy because, at last, a drug had been found that would kill bacteria while not harming humans. The other event was the study of soil antagonism, which suggested possible sources of antibiotics. Scientists had recognized antagonism among soil organisms for a long time. René Dubos, working with Selman Waksman, an American soil microbiologist, on microbial breakdown of cellulose in soils saw many examples of microbial antagonism but did not realize that this might be used in medicine

(Wainwright, 1990). When Dubos moved to a lab in New York, and was asked to find a way to destroy the cell walls of disease-producing bacteria, he remembered the work. Since the soil is the site for most bacterial decomposition, Dubos looked in the soil for microorganisms that could break down cell walls.

The principle behind antibiotics is selective destruction of bacteria. This depends on the ability of the antibiotic to interfere with a feature that is characteristic of bacteria, but not present in animals. Bacteria have distinctive cell walls that are absent from animal cells, so many antibacterial agents selectively attack the cell walls. Ehrlich and Domagk searched among chemical dyes because they knew that dyes attached to the bacterial cell walls. Dubos realized that soil microorganisms made their own chemicals for attacking bacterial cell walls so he screened soil for microorganisms that produced these chemicals. He found gramicidin, an antibiotic more effective than sulphonamides at killing bacteria but also more toxic. Dubos deserves considerable credit for realizing that soil microorganisms were a potentially rich source of antibiotics; he was unlucky not to find an effective one.

The Oxford group

At Oxford, Howard Florey and Ernest Chain planned to study how penicillin and other substances destroy bacteria. Chain had already identified how lysozyme works. Chain planned to study chemical and biochemical properties of each antibacterial chemical, while Florey studied their biological activity (Macfarlane, 1979). When the real power of penicillin as an antibiotic became clear, Florey established a larger group of people to work on it. In 1940 they began to give penicillin to animals to study its absorption, excretion and possible toxic effects. The tests showed that penicillin was destroyed by acid in the stomach, but could be absorbed from the small intestine if it was able to bypass the stomach. It was harmless to animals when injected and was effective against disease, but it was excreted quickly, and large doses, injected frequently, were required. A variety of problems had to be solved. For example, the growth of *Penicillium* had to be speeded up to increase penicillin production, and it was necessary to isolate penicillin chemically from impurities and increase its stability (Macfarlane, 1979).

When penicillin was tried on humans who were dying from disease the results were dramatic. It quickly gained a reputation as a "wonder drug," as exciting stories about wonderful recoveries multiplied. This medical success had such an impact on Florey that he worked incredibly hard to persuade British and American drug companies to join forces and produce penicillin in large quantities. He shared all his knowledge with them, never took out patents and never made any money from penicillin. Penicillin had a major impact during the war, and antibiotics have changed our view of life by reducing risk of sudden death from infectious diseases. Macfarlane has summed up the relative contributions of Fleming and Florey to the discovery of penicillin:

> "Fleming was like a man who stumbles on a nugget of gold, shows it to a few friends, and then goes off to look for something else. Florey was like a man who goes back to the same spot and creates a gold mine" (Macfarlane, 1979: 364).

After penicillin

Three stories about the aftermath of penicillin's success are relevant here. Two involve the development of antibiotics after World War II by soil microbiologists and chemists. The third deals with the strange events that led to fame for Fleming at the expense of others who deserved to share it.

Soil antagonism. Penicillin was effective against Gram-positive bacteria, but had no effect on the Gram-negative bacteria that caused serious diseases like tuberculosis. By the late 1930s Waksman was already isolating antibacterial substances from the soil, so when he read about penicillin in 1940, he began to search among soil organisms for substances that would inhibit Gram-negative bacteria (Wainwright, 1990). He found nearly a dozen potentially useful antibiotics including streptomycin, and other microbiologists have subsequently obtained a large number of therapeutically important drugs by adopting Waksman's methods.

Chemistry. The penicillin molecule consists of two fused rings, and one of them, the β-lactam ring, has a side chain attached. Penicillin will not act as an antibiotic unless the two rings and side chain are intact, but the side chain can be varied to give a series of penicillins with slightly different properties. There were problems with the natural penicillins. For example, natural penicillin was unstable when exposed to acid in the stomach, and some bacteria could become resistant to penicillin by producing the enzyme penicillinase, which opens the β-lactam ring and inactivates penicillin. After the war chemists tried to produce penicillin synthetically. This would allow them to change the side chain, and produce molecules with improved properties, such as stability in acid, and a side chain that was large enough to keep penicillinase away from the β-lactam ring However synthetic production proved to be too expensive so chemists had to take molecules of penicillin made naturally, remove the side chain, and add new ones.

Fame for Fleming. Fleming was treated as a hero for something he didn't do, and is mentioned in high school texts as a great scientist, when he was not. This occurred partly because of the popular press, and partly because the general misunderstanding about science allows people to be easily fooled. If members of the public had understood what would be needed to develop something like penicillin they would have realized that they were hearing only a small part of the story.

Florey and the Oxford group published one paper in 1940, describing penicillin, and another paper in 1941, telling of their clinical tests. The second paper referred to Fleming's discovery of 1928. When news of the medical effects of penicillin was published in newspapers, the head of the laboratory where Fleming worked immediately wrote a letter claiming the credit for Fleming.

Penicillin was big news. Reporters besieged the scientists for interviews and the two men, Florey and Fleming reacted differently. Florey turned reporters away because he was worried that people would ask for penicillin that he could not supply. He also believed that it was wrong for doctors to advertise their work (Macfarlane, 1979). However, Fleming gave interviews readily and was lionized by the press and the public. He did not make up false stories about his part in the development of penicillin, but he made no effort to correct false stories when he heard them (Macfarlane 1979; 1984). He accepted all the honours he was offered, including the Nobel Prize, 25 honorary degrees, 26 medals, 18 prizes, 13 decorations, the freedoms of 15 cities and the honorary membership in 89 academies and societies. He spent the last ten years of his life travelling around the world accepting such honours. Macfarlane (1984) thinks that Fleming could not have created such deception without help, and that Lord Beaverbrook, an important British publisher, created much of Fleming's image.

Accounts of penicillin as they appear in high school texts

A specific example, like the history of penicillin, allows us to compare the real scientific situation with the way it is treated in school textbooks. I will illustrate below, with examples from the discovery of penicillin, some problems in the way historical examples can be used in textbooks.

The idea of learning a topic in science by following its historical development has been used in science teaching for a long time. If the details are carefully selected, history can clarify scientific concepts by showing how they developed. Often concepts are hard to understand when presented in a logical way, but are easier to follow when broken down and presented as they first occurred to scientists. In addition, hidden features of concepts can be clarified by using a historical approach. This method is often used in evolution classes to bring out the differences between the inheritance of acquired characteristics and natural selection.

In 1947 James Conant recommended that history be used more universally in science teaching, but to serve a different function. Rather than teaching the historical development of a topic to clarify scientific concepts, it was to develop an understanding of the scientific process and give a human face to science--to teach *about* science, rather than to clarify scientific subjects.

The discovery of penicillin is commonly given as an example of science. Most of us don't remember the dramatic impact of penicillin on medicine in the 1940s, so that aspect of the story is not emphasized. Instead, authors use it to illustrate how science is done. They stress the value of curiosity in scientists. The following excerpt from the grade 10 textbook, *Pathways in Biology* by J.M. Oxenhorn (1971) is an example:

> "Suppose you were growing bacteria in a Petri dish. One day you notice that some of the colonies seem to clear up and fade away. How would you explain the disappearance? This is what happened in the laboratory of an English scientist SIR ALEXANDER FLEMING in 1928. Dr. Fleming found that his cultures had been invaded by an unwanted guest, a mold of the genus PENICILLIUM. Could there be a relationship? Together with his assistants he was able to remove certain fluids from the mold. When these fluids were injected into bacteria cultures, the bacteria dissolved. Fleming had discovered a natural enemy of germs. Like many a scientist before him, Fleming took his "lucky break" and applied his brilliant mind to it. Could this mold extract kill disease germs? First Fleming tried it on disease germs growing in agar. It worked. Next, he tried small doses in infected animals. It also worked. Finally, infected humans were injected with the fluid and they recovered. Man had found a new weapon to fight disease" (Oxenhorn, 1971: 160).

This account is historically inaccurate; apart from the several factual errors, it gives Flemming credit for work done by Florey and his colleagues. It also gives an oversimplified view of science in which the work, done over a twelve year period by several people appears to have been done over a short period by one man. It does not even hint at the background knowledge needed to make important discoveries and implies that the only prerequisite is a "brilliant mind." Oxenhorn's suggestion that Fleming saw something unexpected and exploited the situation, is wrong. Flemming actually saw something similar to what he had seen before, and he did not exploit it in any depth The most significant thing he did was keep the *Penicillum* culture so that others could work on it later.

The example below comes from a Canadian text.

> "In 1928 a British bacteriologist, Sir Alexander Fleming, was culturing bacteria in Petri dishes as part of an experiment. One day Fleming's assistant noticed that a blue-green mould was growing in some of the cultures. He also noticed that bacteria did not grow near the mould. Fleming became curious; he recognized a problem. Why would bacteria not grow near this mould? Because Fleming asked this question, research was begun which proved that certain blue-green moulds give off a substance that kills bacteria or slows down their growth That substance is called **penicillin**. It was the first antibiotic to be produced and it has proved effective in treating many diseases caused by bacteria. Millions of lives were saved during World War II and the following decades because of this discovery. It all began because Fleming became curious and recognized a problem. Just think for a moment, another person might have thrown out the

cultures because they were mouldy, just as you and I would throw out a mouldy orange!" (Balconi, Davies and Moore, 1980: 7).

Modern science educators are trying to demonstrate "the impact of men, events and scientific fashions on achievements in biology..." (Hurd, 1969: 82). But accounts like these provide a false image of science. Fleming's work is not an example of great science or even of unusual curiosity; he was simply doing his job, which involved looking for antiseptics. There are many other parts in the story of penicillin that do demonstrate great science. For example, Ehrlich made a great intellectual leap in 1910 when he developed the concept of the "magic bullet" and Dubos and Waksman did the same when they realized the possibilities of finding antibiotics among soil organisms. Similarly Howard Florey demonstrated the flexibility and hard work that is needed to accomplish great things. But these men are rarely mentioned in high school texts.

But there is an even greater problem here--the whole image of science is wrong. Science is seen here as a theory-free enterprise in which individuals use their creativity (in the absence of knowledge) to come up with surprising and exciting discoveries. The examples above give the incorrect impression that Fleming was dealing with an unfamiliar situation. Science is not a theory-free activity, but an integrated network of knowledge that is used by scientists to learn new things and create new concepts. Ehrlich and his magic bullet would have been a better example of good science because it shows how he used knowledge from one sphere of science (his understanding of how bacterial stains worked) to solve a problem in another sphere (the need to find a poison that would kill bacteria in tissues without hurting the host tissue). Similarly Dubos and his realization that he could solve a medical problem (how to break pathogenic bacteria down in tissues) by using knowledge he had about soil antagonism (soil bacteria produce substances that break down other bacteria) would have provided an exciting story for school texts. These are examples of exciting and creative science, and they would be much richer and more appropriate examples for science textbooks.

The discovery of penicillin was also used by BSCS as one of their "invitations to enquiry." These are "lessons designed to involve the student in a dialog leading him to an understanding of some phase of scientific inquiry" (Hurd, 1969: 82).

Invitation 16 in the BSCS, *Biology Teachers' Handbook, Second edition* is called "Discovery of Penicillin--Accident in Enquiry." This "invitation to enquiry" is quoted directly, including the initial comment meant for the teacher.

> "To the teacher: Apparently minor unexpected results are obtained in an experiment. They *might* have been due to a mere slip in technique. But the investigator is alert enough and responsible enough to think twice before discarding the apparently minor and apparently technical slip in results. Instead he pauses to consider the possibility that the unexpected result may be due to something new, something not included in existing knowledge or presently used principles and assumptions. The result of this concern of the scientist with something apparently trivial is the discovery of antibiotics.
>
> *To the student*: (a) A bacteriologist in St Mary's Hospital, London, was working with a variety of strains of staphylococcus bacteria, trying to identify the one that was causing an outbreak of infections in the hospital. A number of culture plates

containing colonies of bacteria were on the laboratory bench and were opened from time to time and examined. One plate was found to contain a contaminating mold. The contaminating mold appeared as a white fluffy mass growing near the centre of the plates. Immediately surrounding the mold was a clear zone in which no bacteria grew. This zone was surrounded by a flourishing colony of the bacteria. What might account for the clear zone?

(b) The bacteriologist who found the culture plate with the clear zone surrounding the mold growth soon discovered that when he transferred and grew the mold in nutrient broth in which bacteria grew well, the nutrient broth acquired the ability to destroy several types of bacteria. What new problem thus developed from the investigator's effort to *grow* bacteria?

(c) What further lines of investigation would you suggest?

(d) This Invitation is based on the discovery of the antibiotic penicillin by Alexander Fleming in England, the pursuit of the problem in Italy by Fleming's student, Florey, and the production of penicillin by American scientists working for pharmaceutical companies" (Klinckmann,1970: 193-194).

Discussions *about* scientific processes in the absence of detailed subject knowledge are misleading. Passmore (1980) pointed out that it is no better to teach only details about science than to teach only scientific details:

"It is certainly a minimum requirement of a science course that it should help students to understand what science is like as distinct from giving them a false impression that science is a bundle of tricks and isolated facts which some antiscientists carry with them from their schooling to their grave. But the consequence, too often, is that instead of learning science the student learns something else--the philosophy of science with historical illustrations. Instead of learning by heart scientific formulae he learns by heart, often enough, definitions of theorem, hypothesis, experiment; instead of snippets of information about the behaviour of gases he acquires snippets of information about the behaviour of scientists.... But this much is clear: learning science is very different from learning what sort of thing science is" (Passmore 1980: 98).

But this issue is more serious. Unless the processes of science are taught within the context of subject knowledge, neither the processes nor the subject knowledge will be understood. The processes of science seem to be more important than knowledge when they are presented in isolation, away from the reasons for carrying them out. When illustrations of the work of scientists are part of the larger explanation of a topic, they become part of a larger context--the subject itself, and the activities of scientists become more natural and interesting. Science can then be seen as an enterprise in which both processes and knowledge are important and are interrelated. The methods of science are worth very little without the distinctive knowledge.

SECTION 3

TEACHING METHODS

In this section I will discuss the problem-solving, inquiry, constructivist, STS and traditional teaching methods to bring out what assumptions about science are implicit in each of them, and how these assumptions compare with real scientific research. In this assessment of how accurately the teaching method represents science, I am trying to answer two questions: whether it is valid to emphasize scientific method rather than the subject matter of science, and whether the image of science given by each of these methods is correct.

This section begins with problem solving, specifically with a comparison of the methods and goals used in teaching with the methods used by scientists in research. The chapter on inquiry learning will analyse whether students can make their own discoveries in school laboratories, effectively imitating what is happening in real science laboratories. This will include a description of discovery in science. The chapter on STS includes the issue of moral education. The problem-based approach also raises the issue of the overall construction of scientific knowledge. Can students move in and out of science to retrieve the isolated pieces of information they need to solve social problems? The constructivist theories of learning and teaching brings up the important question: how well can students judge scientific questions for themselves? There is a distinctive culture among scientists that must be considered in answering these questions.

Chapter 8

Problem Solving as a Teaching Method

Educators have identified a variety of goals that might be accomplished by solving problems. I will summarize some of these goals below, then examine studies done on transfer of learning by cognitive psychologists, and finally, describe how scientists solve problems. The main concern is the role of knowledge in solving problems.

Goals for problem solving:

Recently educators have defined a variety of ways of using problems to help students learn. These are described below.

Problems that promote learning within the framework of knowledge. Problem solving in science classrooms is meant to help students learn, but they can learn a variety of lessons. The most straightforward problems support learning within the accepted framework of knowledge. Students can become more familiar with the concepts by practising with problems, or problems can be used to help students learn concepts in the first place--students learn the concepts because they need to know them to solve the problem. While both of these approaches have been popular in education generally, they have also been used in university classes. In classrooms, scientists do not emphasize the definitions of terms like "logistic growth" or "allele." Instead, they teach how to solve selected problems in which these concepts are used. Once students have done enough problems, they become comfortable with the concepts. They know the formal definition of logistic growth, but they gain an intuitive acceptance of this definition from the problems. Kuhn (1977) compared this process to that used when young children learn language. Parents don't teach their children the definitions of words like "duck." They simply correct the child who sees a duck and calls it a bird. The child learns by practising, making mistakes and being corrected. Just as parents try to ensure that their children are given a standard set of experiences in which to learn language, so scientists make sure their students learn how to solve a standard set of problems that represents the kinds of experiences in the discipline. In these cases, the students do not *discover* the concepts or theory by doing the problem, they are simply becoming familiar with the concepts, and comfortable with them, by using them often in practical situations (Barnes, 1982).

Problems that cause students to question and modify their own framework of knowledge. Increasingly we give students problems that force them to question their own framework of knowledge. Constructivist teaching methods, like cognitive conflict and Socratic questioning, encourage students to question their own understanding of a concept, but not the validity of the concept as it is understood by experts. This allows the students to eliminate misconceptions, and is the basis of the constructivist methods discussed later.

Problems that cause students to question the official framework of knowledge. Some experts in education believe that students should be encouraged to question the official framework of knowledge because this develops critical thinking and a real sense of inquiry. They argue that there is progress in scientific research because scientists question existing knowledge, and students should also be encouraged to do so. This will emphasize the tentative nature of scientific knowledge (Perkins and Simmons, 1988; Stewart and Haffner, 1991). Problems can be used to accomplish this. This argument sounds fine, but I believe evidence will show that this may not be feasible.

Transfer of Learning

A series of issues are discussed repeatedly in science education. What are the roles of theory and practice in science? Is science largely a structure of knowledge or is it fundamentally a method or approach to solving problems? In science classes can we teach general problem solving skills or should we teach the detailed content of each discipline and let students learn the problem solving skills on their own? It is odd that this kind of question should even be asked; it puts scientific knowledge and problem solving in competition with each other. These questions are probably asked only because science educators were influenced by a series of studies done by cognitive psychologists in the 1960s to 1970s on problem solving and transfer of learning. I will briefly describe the history of research on transfer of learning and its applications to science education.

Learning theory. In the nineteenth century the doctrine of mental discipline or faculty psychology was strong (Kliebard, 1986). People believed that certain subjects, like science, could strengthen faculties such as memory, reasoning and imagination, in the same way muscles are strengthened with training. Everybody assumed that training in one area could be transferred to others. Scientists who promoted the introduction of science education into schools argued that science would develop different faculties than a classical education, so it was a valuable addition to the curriculum (Youmans, 1867; Huxley, 1898).

In the early twentieth century Edward Thorndike convinced educators that general transfer of learning did not occur, so skills had to be taught directly. From this perspective, a course in science would not develop a person's general mental abilities. This notion was popular with the social efficiency movement. The idea that learning could not be transferred was not questioned again openly until the 1960s, although it was earlier challenged implicitly by the project method of Kilpatrick. If students were to prepare for a changing future by solving problems, then it must have been assumed that they could transfer these problem-solving skills to new problems in new subjects.

In 1960 Jerome Bruner openly suggested that there must be general transferable skills when he distinguished between analytical and intuitive (also called creative) thought. Analytical problem solving proceeds stepwise, but intuition comes from a generalized idea of the problem. Bruner emphasized that, while students needed to understand their subject, they should also be given the opportunity to make guesses based on intuition. He thought that creative or intuitive thought would be increased if generalized problem solving skills were taught. By making this distinction between creativity and analytical skills, Bruner was creating a gap between the rigor and detail of disciplines and the imagination and excitement apparently associated with scientific discovery. Once these two features, rigor and creativity, were distinguished, it was unlikely that anybody outside science would choose to be on the side of rigor. Creativity sounds so much easier and more attractive.

Which kind of knowledge counts most--general knowledge, about how to think and solve problems, or specific detailed knowledge of a subject? In the 1960s and 1970s, studies done by cognitive psychologists seemed to support the position that general skills, like problem solving ability and creativity, could be transferred to other subjects so these skills were most important. It even seemed that knowledge in an area would reduce creativity.

These studies were done using simple puzzles and games. For example in one study, subjects were given a candle, a box and nails and were asked to attach the candle to a wall using the box. The results depended on how the materials were presented to the subjects. If the materials were presented with the nails in the box, the subjects became fixed into thinking of the box as a box, so they had difficulty thinking of it as a stand that could be tacked to the wall to hold the candle. On the other hand, if the box was empty, they were more likely to use it as a stand and solve the problem (Gilhooly, 1988). Psychologists showed that problem-solving did not use just knowledge, but also insight or creativity. People could become locked into a certain way of thinking, and this would keep them from solving the problem. In this example, when people assumed that the box was to be used in the normal way, they were often not able to solve the problem It was as though knowledge of how boxes are used destroyed their creative ability. These kinds of results supported the popularity of concepts like lateral thinking, in which too much knowledge destroys creativity (De Bono, 1969). It was widely accepted in education that students could be taught how to solve problems without learning the details of the discipline, and then they could apply the skills to this and other disciplines. These results were compatible with the ideas of inquiry learning that were popular at that time.

However, it turned out that these studies on problem-solving had a fundamental fault. They used problems that were really just puzzles with no associated subject content (Perkins and Salomon, 1989). By 1975, researchers began to work on problems that were closer to those found in real disciplines like physics. These were disciplines with a knowledge base, in which the problems were more open-ended and complex. In these studies, researchers found that many of the things they had learned for problem-solving with simple puzzles did not apply to academic disciplines. Puzzle problems have very little knowledge associated with them, and that knowledge is stated in the problem. The trick in such cases is to figure out how to apply that knowledge to solve the problem. In real life however, the information required to solve problems is often not present, so much of the difficulty in solving the problem depends on finding the relevant information. The desired goal is usually quite clear in puzzle problems, but it is not at all clear in real life. Therefore when psychologists began to study real knowledge in genuine disciplines, they found that many of the conclusions made for puzzle problems did not apply to problems in academic disciplines (Perkins, 1985; Gilhooly, 1988; Lysenck and Keans, 1990).

Researchers found that, in most areas of life, problem solving depended, not on general problem solving abilities, but on detailed knowledge of the domain (Gilhooly, 1988; Groen and Patel, 1988: Lesgold *et al.*, 1988). Problem solving ability in a subject like physics depends on a large knowledge base in physics. In one study, John Hayes

(1985) examined the compositions of Mozart and found that Mozart became productive only after he had studied for ten years. Furthermore, the pieces he produced early in his career were not as good as those he produced later. Hayes found that this was a consistent pattern, not only for music, but also for art and other disciplines. He concluded that skills like problem solving are not transferable partly because proficiency in some general skills may require vast bodies of knowledge. He noted that it takes years of work to become proficient in a field.

Differences between novices and experts. The conclusions drawn from studies using simple puzzles do not apply to academic disciplines, and general skills cannot be transferred easily. This does not mean that it is acceptable to teach just content within a discipline. Learning is a combination of specific knowledge and general problem solving strategies. It is useless to teach children general problem solving or critical thinking skills independently of a discipline, but it is also not reasonable to teach just the concepts or content and not help them learn how to apply the knowledge to problems. These conclusions became clear from studies done in the 1980s that compared experts with novices in their ability to solve problems (Eylon and Linn, 1988; Confrey, 1990). Researchers found that experts know more in a subject area than novices, but they also organize their knowledge more effectively. Experts store knowledge in "chunks" while non-experts store their knowledge in discrete, disorganized units. For example, the knowledge base of experts in physics includes general principles which they can apply to particular problems. They retrieve these general principles from their memories too quickly for them to be stored individually, so they are probably coordinated in meaningful "chunks". You can improve performance of students by teaching them knowledge organized in this way (Confrey, 1990).

Not only do experts organize their knowledge into larger units, but they also organize it qualitatively better. In one study researchers asked novices and experts to sort problems by the things they thought were most important. Novices tended to organize the problems according to superficial information in the problems, possibly because they did not appreciate what was relevant for solving the problem. In contrast, experts tended to categorize problems using the essential information required to find a solution. Students will be helped if they are taught how to organize their concepts in a way that will allow them to use it more effectively.

Similarly, students benefit when they are taught subject matter and problem solving skills together. In one study in which high school students were taught principles and formulas for the behavior of objects in fluids, they failed to learn how to solve problems from principles and formulas alone. Even the most able students needed some information about how to solve problems, not just general knowledge but detailed procedures on how to solve problems in that domain as well as general methods. Students usually do not have the ability to fill in the gap between the more general idea and the detailed procedure they need to construct to do the problem (Confrey, 1990; Perkins and Simmons, 1988; Reif, 1987).

Solving problems in science - Methods used by scientists

If we understand how scientists solve problems, we may learn what kind of model is appropriate for education. Three models have become popular in schools. The one based on induction is associated with inquiry learning. It pictures scientists collecting observations and generalizing from these to form a theory. The second model, the hypothetico-deductive theory, has usually been linked most closely with traditional teaching methods. It emphasizes how hypotheses are tested but ignores the first discovery stages when scientists decide which hypotheses to test. The third model, based on Kuhn's model of revolutionary science, is associated with constructivist teaching methods. It stresses the exciting changes that occur as one paradigm is overthrown and another replaces it. None of these models places enough emphasis on the enormous background of knowledge that scientists use in their work. Scientists are completely familiar with their subject, equipment and techniques. There is a tendency in school science to ignore this extensive knowledge and assume that students can have the same kinds of experiences, and accomplish the same kinds of results, even while working as scientists in an absence of information. Some researchers in education even suggest that knowledge can stifle creativity.

Problem solving model. A problem solving model would be more appropriate for school science than the models listed above. This model is a composite, combining the hypothetico-deductive model with an initial problem solving portion. The problem solving portion shows how problems can be tackled and solutions found, while the hypothetico-deductive portion of the model spells out how these solutions or hypotheses are tested.

The hypothetico-deductive model describes science as a two-part process: the discovery of an idea and the justification or testing of it. We can break the process down into steps:

1. A question is raised and a hypothesis (or best guess) is formed to explain it.

2. An experiment or set of measurements is designed to test the hypothesis. A prediction is made about what result to expect if the hypothesis is correct.

3. The experiment is done and conclusions are drawn. The actual results are compared to the predicted results and if they are negative (don't match the predicted results) the hypothesis has been falsified. If the results do match, the hypothesis has been supported but not proven correct without further tests.

The hypothetico-deductive model largely ignores the first steps (those involved in forming a hypothesis) and places all emphasis on the later stages (testing the hypothesis after it is formed). It can give students the mistaken impression that hypotheses are formed randomly by pulling answers out of the air, and that there is no quality control in the kinds of answers proposed--almost any hypothesis will do as long as it is tested properly. Scientists tend not to place enough stress on how important it is to form an appropriate hypothesis. They call a hypothesis a *best guess*, but they intend that this casual term will cover all kinds of control factors and limits on what can be proposed. However, only scientists are aware of the knowledge, control factors and limits implicit in the term, *best guess*. Non-scientists tend to take the hypothetico-deductive model literally, and they misunderstand how many limits are really placed on what can serve as an hypothesis. In education we need a model of science that explains more realistically how scientists arrive at answers to problems rather than just how they test those answers.

Constraints "describe" the solution. Solving a problem is a process that takes time. The problem must be proposed, then defined, before it can be answered. Even when it is first proposed, a problem carries conditions and constraints about what the possible answer can be. "A problem itself more or less points the way to its own solution" (Nickles, 1980: 37). Factors like existing knowledge, the context in which the problem occurs, and the standards of the scientific community all point toward possible answers, and limit what an acceptable answer would be. Existing knowledge is always used in solving problems. For example, when chemists initially tried to purify penicillin, they applied their existing knowledge of chemistry to this new problem. They began with methods (like differential solubility in liquids) that had been used successfully in the past to purify similar substances. By doing this, they were making use of methods they knew were likely to work, before searching for methods that had less chance of success. They did not bother with methods that they knew would contradict the principles of chemistry, or would oppose what they had seen work in the past. This was the most rational way to proceed.

There are limits or constraints on every problem (Nickles, 1981). There were limits to the methods chemists could use in the purification of penicillin because it was an unstable compound and its antibiotic action was easily destroyed by heat, acidity and other factors. So the local context (instability of penicillin) set limits on the kinds of solutions acceptable for this problem. Stability increased when the pH was increased, and it increased even more when penicillin was dried to a powder. So part of the solution to the problem of purifying penicillin involved drying it. Since penicillin is destroyed by heat, it had to be frozen and dried under vacuum. These kinds of limits or constraints should be included in our model of science. Any solution to the problem of purifying penicillin must include the conditions that ensure its stability, and must not contradict knowledge gained from other sources. The hypothetico-deductive model ignores the steps that set constraints, so it underestimates the importance of past knowledge, logic and evidence.

The use of analogy in solving problems. There is yet another way in which past knowledge is used. It is common to use analogy (the process of reasoning from similar cases) in solving problems. Some sociologists think it is the main method used in science (Kuhn, 1970, 1977; Hesse, 1980; Barnes, 1982; Knorr-Cetina, 1981; Nickles, 1983). When scientists use analogy in research, they see how a new problem is similar to one that has already been solved. Problems that have been solved are used as exemplars (examples that can be imitated to solve similar new problems). The exemplars are not like rules or theory; the whole process is more casual than that. The exemplar is more like a judicial decision used as a precedent for future cases. Scientists don't deduce answers from an exemplar, and they don't use a general or abstract principle. They simply see that their problem is similar to another situation that can be imitated in some way (Kuhn, 1970; Barnes, 1982).

Once we look for the use of analogy in science, we see it everywhere. For example, Ehrlich developed his idea of a magic bullet in 1910, by seeing the analogy between a dye that would stain bacterial cells while leaving animal tissue unstained and a poison that would kill bacteria while leaving animal tissues healthy. Dubos used analogy when he was asked to find a way to destroy the cell walls of the bacteria causing pneumonia. He looked for antibiotics in soil because he saw the analogy between the problem of breaking down disease-causing bacteria and the normal processes of decomposition in the soil.

Since scientists talk about "flashes of intuition" or "having an idea" instead of "using an analogy," it appears as though scientists are rejecting the old and coming up with totally new ideas out of their imagination. This sounds like creativity, and they support methods like brainstorming that imitate this "creative" phase of science. However, Knorr-Cetina (1981) suggests that the use of analogy is basically a conservative process. An "idea" that a scientist gets is not as much "out of the blue" or as creative as it seems because the scientist is really remembering a similar situation with similar conditions. He or she knows that this particular "idea" or solution worked in another situation so it is likely to work in this case. The scientist using analogy is using existing knowledge.

Although scientists use analogy, they don't mention it in their research papers because research papers contain a logical description of what was done, not a historical description. They may not even remember the analogies they used because they are constantly reshaping both their problem and their image of how they are solving it.

A solution using analogy draws on available knowledge and uses it in a new context; it is not the creation of new solutions, but that does not mean that the use of analogy is not creative (Knorr-Cetina, 1981). The scientist must see similarities in situations that do not normally seem similar, and this is a creative process. It is not just new ideas pulled out of the air in the absence of knowledge; it is gradually developed as a detailed and deep understanding of the subject.

Concentrating on details. Kuhn (1970) pointed out that science only progresses because the scientist has a "restricted vision." By restricted vision, he means that the scientist does not question the paradigm (the accepted theory in his field of study). This accomplishes two things: first, his belief in the paradigm gives him the confidence to work at problems so small and detailed that he is able to make progress; and second, since he does not dissipate his effort by questioning the paradigm, he can focus his concentration and expertise completely on small problems so that he is able to recognize novelty by comparing it with what he knows well and expects to see. Kuhn said

> "Areas investigated by normal science are minuscule, with a restricted vision, but those restrictions born from confidence in a paradigm turn out to be essential to the development of science. By forcing attention upon a small range of relatively esoteric problems, the paradigm forces scientists to investigate some part of nature in a detail and depth that would otherwise be unimaginable. During

normal science the profession will have solved problems that its members could scarcely have imagined and would never have undertaken without commitment to the paradigm. At least part of that achievement always proves to be permanent" (Kuhn, 1970: 23).

On a day-to-day level, science really consists of solving small, detailed problems. As they began their work on penicillin, Florey and Chain were only indirectly dealing with formal theory. One problem that was unimportant in the overall picture, but nevertheless had to be solved before they could progress, was how to increase the quantity of penicillin produced. They tried to increase the growth rate of the mold *Penicillium* by using dishes of different shapes. They also used different kinds of growth medium to find one that would reduce impurities and increase the yield of penicillin. Yeast increased production when added to the growth medium. They managed to make each culture of *Penicillium* produce up to twelve crops of penicillin by drawing off the medium containing penicillin and replacing it with fresh medium. These issues would have been irrelevant if Florey and Chain had not believed that penicillin could be a successful antibiotic, but they were crucial for the ultimate success.

Metaphor (models) in science. Scientific models are one form of metaphor. For example, wave motion is a metaphor for propagation of sound, and the structure of the universe is a metaphor for the structure of molecules (Hesse, 1980). Metaphor is the application of a name or description to an object or situation in which it is not literally applicable. When a metaphor is used, one object or situation is referred to in terms of the other, and each takes on some of the properties of the other. This process can change the meaning of both terms. The metaphor comparing the brain to a computer has changed our view of both.

Metaphor is found most often at the beginning of inquiry because it gives an image that captures some of the things already seen and provides an opportunity to see other new features. When people are learning something new, as both scientists and students do, they need to be able to "play" with ideas, shift them around in their minds and see them from different angles. Metaphors allow this to happen so they are useful in both research and learning. We can see this with Ehrlich's metaphor: "magic bullet" conveyed the image of going directly to the infection and killing it. In 1910 this was a new concept and the metaphor made it easier to understand. DuPreez (1991) suggests that metaphors gradually outlive their usefulness, and are eventually discarded. He believes the computer metaphor for the brain has outlived all usefulness. Models can only be used in science if they are not taken literally. The parts of an atom are not really the same as parts of the solar system. Science students often have difficulty understanding when the model should be taken literally and when it should be taken metaphorically. This is one source of misconceptions.

Science as opportunism. In reality science is scrappy; experiments don't work out, leads may go nowhere, and results lead scientists in unexpected directions. As a result, scientists must be opportunistic--they must have the flexibility to recognize and exploit the opportunities they encounter (Knorr-Cetina 1981). Thomas Nickles defines scientific judgement as "intellectual adaptability in the face of changing circumstances" (Nickles, 1980:38). Howard Florey showed this kind of flexibility and opportunism. He did all kinds of things to make sure that penicillin would be produced, including testing it himself in battlefields in North Africa (Wilson, 1976)

Just because science requires attention to detail and a willingness to solve small problems, does not mean that it is not also imaginative, fast moving and changing. We should be able to project this model of science while still avoiding the impression that it can be done by pulling ideas out of the empty air. Science is not at all like winning the lottery, as it seems in textbook descriptions of Fleming's discovery, and it is not a process of brain-storming (pulling answers randomly out of the air), as it is sometimes pictured. Science is the application of knowledge to problems, a process of reasoning through to a solution, a method of looking for the constraints, and a willingness to concentrate on details. Meaning can only be found at a larger scale if the detailed work is done as well. Science educators will have to decide what they want do they want students to learn only what takes no memorization, is never tedious and is always interesting, or do they want students to learn science even though it means work that is sometimes tedious and depends on detail?

Chapter 9

Inquiry Learning

The inquiry approach to learning remained popular from the beginning of the curriculum reforms in 1960 to the 1980s. It was really an offshoot of the problem solving emphasis that had been popular in education since 1918. However, the problem solving approach of 1930-1960 was tied to learning generally, while the inquiry approach was based on the idea that students learn by using the methods of scientists to answer questions. The organizers of BSCS argued that, because students were learning the methods and ways of thinking within a particular discipline, they would be better able to solve new problems in that discipline while the older problem-solving methods did not have this advantage (Hurd, 1969: 42).

To most people, discovery learning and inquiry mean the same thing--that students learn science in the laboratory by being scientists themselves. This method of teaching is based on the assumption that science is theory-free, and is done by induction. The inquiry approach changes the relationship between students and teacher. In traditional learning, the teacher is an authority figure, even if friendly, because she is the expert with respect to the knowledge. In discovery learning, the teacher is a resource person, someone who guides the student but exerts no authority. The structure of the lesson is also changed in a fundamental way. With traditional teaching the teacher gives students information and this is then used and worked on--knowledge comes first and action later. With discovery learning the student gradually learns the information--activity comes first and knowledge later, and students learn the information for themselves, through activity Finally, what is taught changes. The traditional approach emphasizes subject knowledge while discovery learning emphasizes the activities of science

Evolution of inquiry learning

Initially the terms "discovery learning" and "inquiry" were used interchangeably The basic idea was that students would learn science by being scientists. They would learn by doing rather than by reading or listening to the teacher. The original concept of discovery learning, was gradually abandoned in favour of two other forms of inquiry, the process approach and guided inquiry. Originally processes were used as the *means* of learning the content, but content was still to be learned. But the process approach developed by taking the emphasis on processes one step further. The processes become the *ends* to be learned not the means of instruction it is not the content of science that is taught, but the processes of science. This approach is most common in elementary and junior high. Guided inquiry moved in the opposite direction with a greater emphasis on content. Students are still to learn content by using the methods of scientists, so they still learn theory by discovering it for themselves, but the teacher gives guidance to make sure this happens and gives it a helping hand when it does not

Process approach. The process approach emphasizes the methods and attitudes of science rather than scientific knowledge (Wellington, 1989). It has moved so far away from the knowledge of science that it brings the definitions of science into sharp relief

Is science a body of knowledge or a method of learning about the world or is it both?

Guided inquiry. Guided inquiry developed as teachers realized that students did not discover concepts as expected, and began to give more guidance, making sure that students understood the concepts by the end of the lesson. Guided inquiry is a compromise; the teacher determines what happens, but does so, not by giving students information, but by asking questions that are designed to *lead* students to the right answers. But it tries to keep certain advantages: that students appear to have control over their own learning and that they learn by questioning. This contains an element of artifice because the students *seem* to be in control of their own learning while the teacher is actually in control. The timing and method of presenting information differs from traditional teaching. With guided inquiry, the student is expected to know roughly the same information in the end, but she gets there differently. The information is never given in a straightforward manner, but it may eventually come from the teacher. It comes as answers to a series of questions asked by the teacher. The example below demonstrates guided inquiry.

> "A teacher goes into a lesson knowing the intention is to investigate the frequency with which water beetles come to the surface and the concentration of oxygen in the water. All the apparatus and materials required for this work has been ordered and is available but not in view of the students. At the start of the lesson the students are asked to look at aquaria that they have set up in a previous lesson and to make as many observations as possible. After a few minutes these

observations are collected and listed on the board. The teacher selects (apparently arbitrarily) for further investigation an observation made by several students that beetles are darting up and down. The area of interest has been defined by the teacher. Now students are asked if they can think of reasons why the beetles keep coming to the surface of the water and a further list is drawn up which includes: to get air, to get food, because they are attracted to light and to get warmer. A further 'random' selection is made by the teacher that 'to get air' seems a reasonable area to investigate. The problem has now been stated by the teacher. The students are now asked to design an experiment to investigate the problem and from their designs a common strategy (determined by the teacher before the start of the lesson) is selected. It is plain to see how the rest of the lesson may develop with the students fully involved but with the teacher firmly in control of the direction the lesson will take." (Lock, 1990: 69)

What is possible with inquiry?

Inquiry *seems* to satisfy all the major aims of science classes in one stroke. Ideally, students can learn scientific theory for themselves, learn about science, have direct experience in the lab and become motivated, all at the same time, by using inquiry methods. However, it is hard to translate these ideals into reality with inquiry. Therefore, I would like to discuss several questions about what inquiry can accomplish: Can students learn important scientific concepts by discovery? What is discovery in scientific research--this process that students are trying to imitate in inquiry learning?

Is it possible to recreate the excitement of discovery for students? What role does scientific knowledge play in discovery? What is the relationship between knowledge and creativity? Which is more important and more characteristic of science, knowledge or process? Finally, does inquiry improve motivation of students?

Can students discover important scientific concepts?

This first question does not really relate to science itself, but to learning. Jerome Bruner (1960) said that students can discover science for themselves. But can students learn in this manner? Not if he means that the school boy will discover the principles of physics or biology for himself. This point has been made often in the last century by moderate educators. For example in 1929 Westaway said:

> "A boy never 'discovers' a principle, and it is doing him a disservice to let him think he does" (Westaway, 1929: 26).

and in 1980, Passmore said:

> "A pupil's school experimental courses inevitably simplify the actual situation in which a physicist finds himself and may well leave the pupil with a quite false impression of what scientific discovery is like. The notion that a child can somehow 'discover for himself' what it took physicists centuries to discover is manifest nonsense" (Passmore 1980: 68).

Scientists have an extensive theoretical background that they did not discover for themselves. This point was made in the most compelling way in 1968 by a philosopher of education, Robert Dearden. He cautioned against the idea that children can abstract theory from experience. Science, mathematics and history, he said, "are achievements of long inquiry (which) do not lie wide open to view" (Dearden, 1968: 108), so

> "To initiate a pupil into the world of human achievement is to make available to him much that does not lie upon the surface of his present world" (Dearden, 1968: 108).

Dearden said that theoretical concepts, like those found in mathematics, science and history, organize our ordinary commonsense experience and increase our intellectual understanding of it. It is impossible even to understand what one sees without the appropriate theoretical understanding.

He argued that child-centred theorists are incorrect in suggesting that we can learn mathematics and science directly from our surroundings. What is visible to an observer who understands a theory is simply not apparent at all to those who don't know it. As adults, we forget what it is like not to know, so we don't realize that children are not seeing the same things in nature that we can see. Dearden was convinced that children could not start with ordinary situations and grow outwards to theoretical understanding, as had been proposed. As he put it: "... theoretical studies kick away the ladder by which they climbed." Children can learn theoretical concepts only from teachers because there is a degree of discontinuity between theoretical and commonsense concepts

> "Theoretical concepts are connected in systems that have been elaborated and modified by a long tradition of inquirers and they simply do not exist outside such communities. They originate in and percolate out from such traditions of inquiry, they do not originate afresh and spontaneously in the individual minds of each

generation of eager and curious children granted only a suitable material environment" (Dearden, 1968: 124).

The real problem with guided inquiry is that it tries to accomplish too much. It is valid to let students experience inquiry--to have all the pleasures of working on open-ended problems. It is just not reasonable to believe that students will discover scientific concepts for themselves. Guided inquiry tries to teach theory, and accomplish all of the other functions of a science class, in one mechanism, and that is not possible. We should not use inquiry in laboratories as a means of learning theory, but we can still use it to work on smaller topics that interest students. Part of the laboratory activity should be spent on projects or experiments in which students are carrying out their own inquiry and making their own decisions. But these should be minor projects where the answer is not important. We should not expect these activities to accomplish much in terms of theory. They are most effective when everybody relaxes and enjoys them as simple problems to be solved, and opportunities to try things in the lab, and nothing more.

Discovery Within Science

Discovery is what science is all about. This single word represents all that is exciting and interesting about it. Discovery compensates for the tedious work, and makes science into an adventure. Science educators keep trying to reproduce the thrill of discovery for their students, yet somehow their efforts fail. The term, "discovery," is used in such a variety of contexts that it actually has several meanings in science. Perhaps if we can identify more closely what scientific discovery really is, we will find a better way of presenting it to students. Therefore, I will try to identify the different meanings of discovery, and find the different contexts in which it occurs

The usual view of discovery

We make common assumptions about discovery. Famous discoveries are often described as coming from sudden insight, or even dreams. Discovery seems to be too individual and unpredictable to be studied. It seems to be instantaneous and passive, we see something for the first time. Recently these assumptions have been questioned. It has been suggested that discovery is not an instant process, but something that occurs over time (Kuhn, 1977), and not such an unpredictable process, but one in which knowledge and judgment take part (Barnes, 1985; Nickles, 1989a). Similarly it is not at all passive; action is a key factor (Hacking, 1983; Gooding, 1989a) There is even a social factor involved in discovery because something is only defined as discovery if it is given public approval. Individuals "discover" things all the time that don't count as discovery in official terms (Brannigan, 1981)

The discovery of the structure of DNA in 1953 fits the popular image of discovery as a single event with no internal structure, but the image is wrong. This discovery was unusual because scientists knew in advance what they were looking for, and the final result was not in dispute. Even then, a proper account of the discovery of DNA should include all the steps, taken by many other scientists, that led up to the final step of Watson and Crick. Most discoveries are more diffuse than this, because they come as a surprise, and are not predicted in advance. We often can't even isolate when the discovery actually occurred. For example, when was penicillin discovered--in 1928 or 1940? It is convenient to describe discoveries as having occurred at a certain time, but it is also incorrect. Fleming discovered penicillin--as an antiseptic (a chemical that kills bacteria) in 1928, but he did not discover penicillin--as an antibiotic. That was done by others twelve years later. And we value it as an antibiotic, not as an antiseptic. So Fleming discovered only a small component of penicillin. Kuhn (1977: 172) has pointed out that something is discovered only if the phenomenon is produced, *and* if the discoverer is also aware that he has discovered something and what it is. He points out that the process of discovery almost always extends over time and often involves a number of people. By these criteria, penicillin was discovered from 1928 to 1940 by the combined efforts of at least three people, Fleming, Florey and Chain.

Kinds of discovery

Discovery should not be used as a blanket term because there are at least three different kinds of discovery, each with its own set of characteristics. Discovery can occur when something is found that was predicted by theory in advance (e.g., structure of DNA). In such a case it is almost the end point or conclusion of the process, and comes as no surprise. On the other hand, discovery may consist of finding something not seen before and not expected. The initial discovery, by Frederick Griffith in 1928, that DNA could transform bacteria from one form to another, fits into this category because it took the scientific community by surprise and did not support their theory that genetic material was protein (Judson, 1979). When this kind of discovery occurs, it is the beginning of a process. Discovery can also be the cognitive process in which a new explanation is found for an old phenomenon. This kind of discovery is related to learning generally, and can depend much more on mental activity than on experiment. This third kind of discovery (theory-bound discovery) is something that occurs within the mind of the discoverer. It is a new insight into nature, and, while it can be accompanied by new evidence, it can also occur even in the absence of new evidence simply because an individual learns to look at a phenomenon in a new way. It is important in education because the same thing happens in learning. This will be described later because it is the kind of discovery that supporters of the constructivist teaching method hope to promote in students.

Discoveries that are expected

Many discoveries are first proposed as theory. Then experimental evidence is gathered that confirms the theory, finds new examples of the phenomenon or clarifies the phenomenon. The discovery is only an explicit demonstration of something previously predicted (Kuhn, 1977). The discovery of streptomycin and other antibiotics by Selman Waksman in 1944 fits into this category of "discoveries that were expected." Scientists learned from sulphanilamide drugs that certain chemicals are toxic to bacteria and non toxic to humans. They learned from penicillin, that microorganisms produce such chemicals. Tney knew from many observations of antagonism among soil organisms that the soil was potentially a good place to find antibiotics. Therefore this discovery of streptomycin came as no real surprise, and it can be precisely dated.

Could students make (or imitate), these kinds of discoveries in school laboratories? The closest thing in schools to this kind of discovery is the confirmation that might be found in a traditional class where students are taught theory, then asked to do experiments to confirm it. Situations could be created in which students apply the concepts they have learned to new situations. Inquiry learning does not promote this kind of discovery since it does not teach theory in advance of laboratory work.

Frontier science--Discoveries that come as a surprise

Scientists sometimes find things in nature that they have never seen before, and have no theory to explain. These discoveries come as a surprise, and lead to the development of new theory. We could call them nature-driven discoveries because they occur when something new in nature is revealed to a scientist. They are sometimes found when new equipment or techniques are developed that allow scientists to "see" nature in a new way. David Gooding calls this "frontier science" (Gooding, 1989a: 126). His examples come from the work of Faraday, the nineteenth century scientist who discovered electromagnetism. Faraday left such complete laboratory notes that it is possible to see how his concepts developed, even before he was able to put them into words I will summarize Gooding's description of frontier science (Gooding, 1982, 1986, 1989a, 1989b).

Discovery in frontier science takes time, and consists of a number of steps. The first step is interaction between the scientist and nature; the second involves finding a way to communicate the discovery to other scientists; and only then does a process occur in which the new observation and existing theory are reconciled, and an interpretation is formed that can be tested.

Interaction with nature. Occasionally a scientist will see something he does not understand. It may be something he did not expect to see and cannot explain. He learns more about the phenomenon by "playing with it" or doing things that will give results he can describe to others. When this happens, the scientist lives in a state of uncertainty and Gooding calls (1989a) the experience "fluid".

Communication with other scientists. Next, the scientist describes his initial experience to other scientists, so they can see the same phenomenon. He communicates by means of a "construal," a description given before you really have words to describe what you see, and before you can explain it with theory. As scientists communicate back and forth they form a series of construals or preliminary descriptions of what they are seeing, each construal becoming more articulate and precise than the one before, and each providing more guidance on where to go next.

Formation of an interpretation. Gradually the scientists begin to form an interpretation of the new phenomenon. The interpretation links the new phenomenon with existing theory. Finally, the point is reached when the explanation for the phenomenon can be tested.

Frontier science comes before we reach any stages of science normally referred to as part of the scientific method. The final interpretation formed in frontier science is really the hypothesis that can be tested. Frontier science consists of the initial realizations and explorations of a scientist before he can even begin to define a problem.

Some of the features of frontier science can be seen in the discovery in 1957 that led to the production of semisynthetic penicillins. A company in Britain discovered a strain of *Penicillium* that produced only part of the penicillin molecule--the central ring structure. These scientists were producing large quantities of natural penicillin. They measured the exact quantity produced by two methods; one measured it chemically, and the other was a biological assay which measured the number of bacteria killed. In 1957 they found that the two methods gave them different estimations of the quantity of penicillin produced by one strain of *Penicillium*. The chemical method told them that they had more penicillin than was indicated by the biological assay. They had seen this effect before, but this time the discrepancy was too large to ignore. There were many possible explanations. Perhaps their methods of measuring penicillin were faulty, or perhaps the mold was producing defective penicillin. They examined their problem, and tried many things. At one point they added a solution containing the molecules that normally form the side chains of penicillin to their defective penicillin. This produced biologically-active penicillin. They hypothesized that their strain of *Penicillium* was producing only the central rings of penicillin (without the side chains), and they confirmed this with chromatography (Wilson, 1976).

Recreating discovery in schoolrooms

Frontier science is probably what supporters of inquiry learning, and all teachers, want their students to experience, so we should ask whether it is possible to recreate the excitement of discovery for students, and what conditions are most likely to lead to it?

The most common answer given in science education would be that we can recreate discovery for students by encouraging them to be creative. A special aura has developed around the word "creativity" in science education. However, this image of creativity in science is a mirage, and efforts to recreate it in science classrooms are, not only misguided, but possibly damaging. Students are fed images of creativity in science in textbooks like the one below:

> "The real impetus to the scientific method and the formulation of theories and principles is curiosity about nature. The truly creative scientist always keeps an eye open for the bizarre, the unexpected, the chance observation that may lead to sudden new insights. For instance, in 1928 when Sir Alexander Fleming noticed "halos" of killed bacteria around certain moulds growing in culture dishes, he wondered why. His hypothesis that the moulds produced an antibacterial agent led to the discovery of penicillin, an antibiotic that has saved millions of human lives." (Hopson, J. and Wessells, N.K. 1990. *Essentials of Biology*).

This account misrepresent the discovery of penicillin by suggesting that the halos around the mold were unexpected and Fleming investigated them because he was creative and curious. In fact the halos were not unexpected; Fleming had seen the same effect before, specifically when he discovered lysozyme. It was good work to isolate penicillin but it was familiarity, rather than curiosity, that allowed Fleming to recognize that he had an antiseptic in his culture and try it out on other cultures. This passage gives the impression that if an individual just develops his creativity, he, too, will make startling and important surprise discoveries, even with no background knowledge or experience, when the opposite is true.

Does knowledge inhibit creativity?

The emphasis on creativity can be detrimental when the impression is given that creativity and knowledge are in opposition to each other. Some people believe that knowledge stifles creativity in science. It prevents scientists from seeing things in new ways and colours their judgement (Feyerabend, 1975). Some say, therefore, that we should encourage students to be creative in science classes by limiting the amount of knowledge we give them, encouraging imaginative thought and ignoring existing traditions. Members of this group have changed the meaning of creativity from "extraordinary achievement" to "a mode of thought or a process" (Bailin, 1988). They also emphasize that creativity involves breaking established patterns, and they associate it with rapid change and revolution. Supporters of this new view of creativity believe that, not only knowledge but also skills and rules associated with a scientific tradition inhibit creativity. They define two kinds of thought: creative thought which is imaginative, irrational, suspends judgment and breaks rules; and normal thought which is logical, rigid, depends on habit, and includes judgment (Bailin, 1988).

Bailin and Passmore (1980) are correct when they say that these views are false. However, Passmore, like most other educators, worries that it is more common in science education to ignore creativity than encourage it:

"In science, in contrast, he (the child) generally learns from a text-book, not from

> the imaginative writings of great scientists. In discussing scientific discoveries, furthermore, his text book often proceeds as if these discoveries were either 'inductions' from experiments or deductions from general principles, on the false assumption tnat the only sort of 'going beyond' which is permissible in science is strict inference. (Some text-books have tried to correct this situation)" (Passmore 1980: 160).

While Passmore is correct that science is too often taught without any allowance for creativity, he is probably also too optimistic if he thinks a child (or anybody not educated in that field) could understand the imaginative writings of great scientists

I will demonstrate, first, that the incorrect ideas about creativity have a real impact in biology education, and second, that they are detrimental. DeBono described two methods of thinking, lateral thinking which is characteristic of creative thought, and vertical thinking which is typical of logical thought. Lateral thinking requires a suspension of judgment and involves going outside the existing framework for the solution to a problem. DeBono argues that our normal logical thinking tends to be inflexible and limits creativity. Creativity, when defined this way, sounds so appealing and this is sometimes translated into action in our schools by encouraging students to use brainstorming. The idea behind brainstorming is that judgment should be deferred as ideas are produced, so that the students will not feel that their ideas are silly (Hare, 1993). The Nova Scotia Curriculum guidelines for biology (1990 and 1993) list brainstorming as one teaching activity. Students are asked to generate responses to an idea or a problem without reflecting on them.

"Investigating questions such as, 'How can we reduce energy consumption in Nova Scotia?' 'How can we hook up three bulbs and two batteries to get different degrees of brightness?' or 'Why do you think some people are concerned about genetic engineering experiments?' should begin with students brainstorming ideas" (Curriculum Guide No. 118, Nova Scotia Department of Education, 1990: 38).

After the ideas have been generated by brainstorming, they must be discussed and judged. Hare points out the danger that students will think that simply producing many ideas, even mediocre ones, will earn a student a reputation for being imaginative (Hare, 1993: 151). A further difficulty in science education is that students may believe that it mirrors the way scientists arrive at testable hypotheses. There are limits and constraints associated with every problem in science, where it is more effective to find out something about the problem, then look for solutions. Hare warns against establishing a "dubious dichotomy" in assuming that we have to "play down critical reflection to allow our imaginations to flourish" (Hare, 1993: 151).

Essential tension rather than revolution

The idea that students can come up with dramatic and creative ideas by ignoring logic, judgment, knowledge and past experience is also associated with the image of science as revolution. Revolution is a metaphor or model used to describe science But models never fit the thing they describe perfectly. The metaphor of science as a revolution has been taken too far, and it has been taken more seriously by educators than by scientists. In fact, one of Kuhn's (1970, 1977) most interesting theories was the "essential tension". He stressed that discovery in science is only possible if the two components, flexibility and tradition, are intimately connected. Scientists will only succeed if they have these two factors pulling in either direction. There is an irony that his notion of a scientific revolution should have such appeal, when the much more subtle and interesting view of science as tension between flexibility and tradition should be seldom noticed or commented on. The idea that it is the tension between change and tradition that leads to discovery, is the same as saying that creativity and knowledge complement each other. All discoveries have their roots in existing problems and theories, they are a modification of the past rather than a break from it.

Knowledge--crucial for discovery

Knowledge and creativity are in conflict. Kuhn (1970) points out that their belief in a theory or paradigm does cause scientists to resist seeing something new, and such resistance is beneficial for science because it keeps scientists from being too easily distracted, and changing their points of view too often. But then he says that knowledge is necessary for discovery, because if scientists do not have theories of what to expect, they will see nothing at all.

> "One suspects that something like a paradigm is prerequisite to perception itself. What a man sees depends both upon what he looks at and also upon what his previous visual-conceptual experience has taught him to see. In the absence of such training there can only be, in William James's phrase "a bloomin' buzzin' confusion" (Kuhn, 1970: 113).

He describes the paradox that he calls "the radical-conservative essential tension". we are not able to observe unless we have a theory that tells us what to look for, and yet we will be resistant to seeing anything other than what we expect. However, although theory tells scientists what to look for, it does not limit what they actually see. Scientists can have a theory which makes them confident that they will see one result, and yet still be able to recognize anomalies when they occur. This happens because having a theory, with associated expectations, may partially blind you, but it also focuses your attention. And this concentration on details leads to success.

> " Novelty only emerges because the man knowing with precision what he should expect is able to recognize that something has gone wrong" (Kuhn, 1970: 65).

We can still see things we don't expect. In fact theory helps us see something novel by focusing our concentration on details in the first place. When we encounter novelty, theory makes it more visible for us by giving us a measuring stick that we car compare the novelty to.

Creativity and knowledge are not in competition, they *complement* each other; you are *more likely* to find creativity where you have knowledge. This is particularly true for science because all discoveries have their roots in existing theory. There are few problems that can be tackled in science without extensive background knowledge. The creativity of science is a small scale, detailed, application of knowledge to new problems. This is said beautifully in the comparison with rock climbing below.

> ".. simple solutions come only from detailed understanding of the complications. Skill at recognizing and using simplicity comes no more easily than skill at rock-

climbing. What looks to a novice like an impossibly sheer wall requiring crampons, itons, and belays may appear as easy as a ladder to an experienced rock climber. It is only when one has enough skill to appreciate the difficulties that the ascent becomes simple. Simplicity is arrived at, not by simplification, but by the most thorough understanding of the principles involved. Do not confuse simplicity and simplification" (Root-Bernstein, 1989: 418).

The dangers in promoting creativity at the expense of knowledge

Jaques Monod, a famous molecular biologist said:

"Too many people equate creativity in science with sloppy thinking and rule breaking. On the contrary, the severest scientific exactitude, rather than forbidding, actually authorizes and encourages enthusiasm for the boldest speculations. Therefore, the wilder the ideas you wish to propose, the better they must be anchored by the accepted techniques" (Monod quoted by Root-Bernstein, 1989: 415).

Hayes (1985) warned of the dangers faced by students who buy into the current ideas about creativity. He found that composers like Mozart produced more, and better work once they had studied for some years because large quantities of knowledge are essential for skilled performance in music. He warned that, if we allow students to think that their ability lies just in talent and creativity rather than effort, some students will become discouraged and give up too soon, and others will become lazy because they believe they can accomplish great things with their creativity, and need make no effort.

Neither group realizes that effort will lead to real improvement.

Are the processes of science special?

Is it the processes of science or scientific knowledge that makes science so special? The following definition of science (taken from a textbook on science methods for education students) is typical of the view taken by educators.

> "Science is a *way of knowing* that involves the pursuit of the understanding of the natural and physical world. It results in a body of knowledge obtained through inquiry, which is aligned with observation, experimentation and prediction. Science is also a *way of thinking* that promotes an attitude of objectivity, self examination, and a search for evidence" (Collette and Chiapetta, 1989: 235).

This definition emphasizes the methods and attitudes of science, while it speaks of scientific knowledge as a *result*. These kinds of definition are misleading. Science is not fundamentally a method, it is really an integrated system of concepts that explain the natural world. Later, I will discuss the role of scientific knowledge in science; I will explain here why the processes and methods of science are not so special

The processes used in science are not distinctive of science; they are the same processes everybody uses in daily life, so everybody knows how to use them already (Millar, 1989a). If you teach scientific processes like observing, etc., students are not really learning anything new. The distinctive feature about scientific method must be seen as the process of applying knowledge to new situations. Since knowledge plays such an essential role in the method of science, it is incorrect to differentiate between the processes and products of science. Knowledge is not a "product" of science, it is the most important part of the process.

For a long time scientists have been saying that scientific methods are not distinct or unusual. In 1854 Huxley said that the results of science were gained:

> "By no mental processes other than those which are practised by every one of us, in the humblest and meanest affairs of life". Therefore science was "nothing but trained and organised common sense, differing from the latter only as a veteran may differ from a raw recruit" (Huxley, 1905: 45 quoted by Jenkins, 1989: 23).

And in 1949, Percy Bridgman, winner of a Nobel prize in physics said:

> "It seems to me that there is a good deal of ballyhoo about scientific method. I venture to think that the people who talk most about it are the people who do least about it. Scientific method is what working scientists do, not what other people or even they themselves may ask about it. No working scientist, when he plans an experiment in his laboratory, asks himself whether this is being properly scientific, nor is he interested in whatever method he may be using as *method*.... The working scientist is always too much concerned with getting down to brass tacks to be willing to spend his time on generalities. Scientific method is something talked about by people standing on the outside and wondering how the scientist manages to do it. These people have been able to uncover various generalities applicable to at least most of what the scientist does, but it seems to me that these generalities are not very profound, and could have been anticipated by anyone who knew enough about scientists to know what is their primary

objective. I think that the objectives of all scientists have this in common--that they are all trying to get the correct answer to the particular problem in hand. This may be expressed in more pretentious language as the pursuit of truth" (P.W. Bridgman, on "Scientific Method," *The Teaching Scientist*, Dec. 1949: 23 quoted in Brandwein, Watson and Blackwood, 1958: 12-13)

Scientists are excited by the subjects themselves not the methods, but some educators seem to think that the methods are interesting, not the subjects. This discrepancy in priorities may lead to serious problems in science education.

Millar and Wynne studied public understanding of science in Britain after the Chernobyl accident and concluded that neither teaching only content nor only process would supply members of the general public with a real understanding of science. They found that members of the public seemed to think that, if you follow the clear rules of science, you will produce valid scientific knowledge. They expected scientists to answer questions with a kind of precision that science is not capable of. In addition some groups tried to measure radioactivity in school yards, apparently believing they were doing useful science simply by gathering numbers, even though they ignored calibration, standards, interpretation and background theory. Science is not as simple as most individuals believed. The issue was not that individuals had insufficient knowledge, but that they had the wrong kind of knowledge. When students are taught only content, they do not understand how scientists obtain facts; when they are taught only processes, they believe that science is just a series of foolproof methods which will give facts if followed. They fail to understand the role of theory in science or the structure of science as a complex interlocking structure of theories. Since they do not understand science, they have naive views about what they can expect from it, as happened with Chernobyl (Millar and Wynne, 1988).

Motivation and inquiry

Atkinson and Delamont (1977) compared guided inquiry to bedside teaching in medical schools. They concluded that inquiry learning in schools will not reproduce the intensity and excitement of real science. In addition guided inquiry requires that both teacher and student *pretend* they are doing real science when they are not.

Medical students have two kinds of experiences in hospitals, teaching rounds and work in the emergency ward. Students follow a doctor on teaching rounds that are designed to teach medical students, and are separate from the management of the patient. Medical students also work as assistants overnight in emergency wards, and participate in the "real" work of the hospital. They call the emergency sessions *hot* medicine and the teaching rounds *cold* medicine Hot medicine occurs at the time of the consultation and treatment of the patient, while cold medicine takes place after the consultation, but employs material taken from it. The hot situations are more effective in teaching. Patients have already been treated by the time they are seen by students on the teaching rounds. The illness is no longer fresh and diagnosis has already been done so the teaching rounds are a contrived situation imitating the hot situation, not reproducing it.

The teaching rounds give medical students the same kind of experience that guided inquiry gives science students. On teaching rounds students are required to "discover" the right diagnosis for each patient, and in science classes they are expected to "discover" the right concepts. The comparison of hot and cold medicine clarifies that guided discovery is "cold science," but science students never have access to "hot science"; their teachers probably didn't either.

There are important problems with "cold science" and "cold medicine." This kind of teaching requires stage managing. All participants must pretend they are doing real science, when they are not. In science class the lesson will only work if the teacher treats the experiment as if it were hot science, and the answers are not already known. The students must pretend it is hot science, but they must not really believe or act as though it is hot science, or it will fail. As a teaching strategy, guided discovery is difficult to sustain, and there are many points at which it can go wrong. Teachers using it need to engage in artful stage-management if they are to bring it off successfully. If any of the students openly mention it, it will fall apart. In addition, it is a problem if the "stage machinery" becomes too visible. For example, if students do not come up with the required answer, the teacher may have to become too visible in pushing it in the direction she wants.

Atkinson and Delamont also compared guided inquiry to information games like twenty questions, where panellists search for an answer by asking questions. The idea is to hide the answer, but there is embarrassment if the panellists do not finally arrive at the correct answer. In education, the object is to make the answer appear at the right time in the right manner. The students must "go through the motions" of correct medical or experimental procedure. This kind of deception is part of teaching generally, but there is a risk that it becomes dishonest if it goes too far.

The charm and the disappointment of inquiry

Inquiry seems to be such an attractive method for the student, mainly because it is satisfying to be in control of your own learning. We should always encourage inquiry among our students and should demonstrate it in our own approach. The problem arises when we frustrate our students by expecting them to learn too much by inquiry.

> "A beginner in science may "discover" a test-tube hidden in a drawer, but he will rarely or never discover a principle lurking in a group of facts" (Westaway, 1929: 26-27).

It is dishonest to let students think they are discovering theory when they are not, and honesty is crucial in teaching. Guided inquiry is supposed to be open-ended--like real science--but it is not (Wellington, 1981). Learning science means learning the accepted scientific theory. This can only be done under control of the teacher. If the students are allowed to work in an open and unrestricted way they are not likely to learn any theory. There is a basic conflict: you can learn theory or you can carry out inquiry with freedom, but you can't do both at the same time. Inquiry will always haunt teachers. There is such charm in the idea of inquiry learning, but disappointment in the reality.

What should we do in school laboratories?

Laboratories can satisfy a number of goals. They can increase understanding of the concepts of science, improve motivation and self esteem, develop observational and other practical skills, increase tacit knowledge of science and develop problem-solving skills. But laboratories cannot do all of these things at the same time. The problem with guided inquiry is that it tries to do too much: it tries to teach theory, and accomplish all of the other functions of a science class in one mechanism. I will look at each of the goals in detail and discuss what can be accomplished.

Increase understanding of the concepts of science. Theories should be taught to students in class in a fairly straightforward way, but practical work can be used to illustrate theory and give it reality. In the laboratory students have a chance to manipulate ideas and work with them. Experiments are valuable when they allow students to use their knowledge in a new situation and to manipulate ideas. This can be done with an inquiry approach by introducing experiments based on theory known to the students, but investigating details not known to them.

Woolnough and Alsop (1985) made the surprising, but intriguing, suggestion that we should not use practical work to illustrate theory because it is a waste of time trying to teach abstract concepts through concrete practical experiences. By artificially tying theory and practical work together, you have to reduce the sophistication of the ideas to match what can be accomplished practically, and this insults the intelligence of students. They add that practical work adds a "distracting clutter of reality". Many scientific theories are "elegantly simple," but when students are carrying out an experiment, the elegance is hidden by the "experimental trivia" that distracts them from the underlying concept. Students are submerged in details and measurements, and lose sight of the underlying theory. "The distracting clutter of reality" hinders a "search for patterns." Since their working memory is overloaded, students get bogged down in details, and learn nothing (Woolnough and Alsop, 1985:38).

However, Millar (1989a) points out that science is an interplay between theory and experiment, so their total separation in classrooms is not desirable. Tobin *et al.* (1990) added that the teacher should have class discussion after all practical work to clarify what happened and make sense of the experience. Class discussion should counteract the problems described by Woolnough and Alsop.

Improve motivation, self esteem and socialization. All teachers know that you cannot keep students still for too long. Practical activity gives them variety, activity, a chance to socialize and a chance to t_ things for themselves rather then just hearing about them. It engages students in the activity, and gives them ownership over their knowledge, so it is likely to increase their interest and motivation if done properly. In addition it gives them a chance to develop self-esteem and confidence by allowing them to undertake the problems and activities themselves (Hodson, 1988b). It should show students that **they** can manipulate and control events, and that **they** can investigate and solve problems- or at least tackle them.

Develop practical scientific skills and techniques. It is valuable to allow students to develop practical scientific skills and techniques such as observation, measurement, estimation and manipulation. However, it is important not to encourage an atomistic approach and allow students to think that this is all there is to science.

Tacit knowledge of science. Some of the knowledge used by scientists cannot be described in words, and is called *tacit knowledge* (Polanyi, 1958). The standard example of tacit knowledge is the ability to ride a bicycle. We learn how to ride a bicycle by doing it, not by reading about bicycles. Tacit knowledge is not openly incorporated into our theories, and is never articulated. It is acquired directly through our senses, and used directly in the laboratory. Practical work in school laboratories allows students to experience science, and connect scientific words to some concrete activity. For example, students can read or hear about photosynthesis, chromatography and spectrophotometers, but they learn about these in a totally different way when they separate chlorophyll from other pigments using chromatography, then use a spectrophotometer to measure absorption of the pigments at different wavelengths. There is a physical sensation in seeing things happen that means a great deal. This is a strong reason for using experiments in science education.

Development of problem-solving skills. How can we allow students to glimpse the pleasures of working on open-ended problems and learning for themselves, as intended by inquiry learning? Just because students cannot discover theory through activities, does not mean that they cannot inquire about a topic that interests them. Part of the laboratory activity should be devoted to projects or experiments in which students are carrying out their own inquiry and making their own decisions. They can be encouraged to work on open-ended problems where it does not matter which answer they get. It is important not to expect these activities to accomplish too much (Layton, 1990).

Action is one of the most important features of discovery (Gooding, 1989a). Hacking (1983) noted that work in the laboratory has unanticipated outcomes because experiments don't work in the straightforward way that non-scientists imagine. He said:

> "As a generalization, one can say that most experiments don't work most of the time. To ignore this fact is to forget what experimentation is doing... To experiment is to create, produce, refine and stabilize phenomena. If phenomena were plentiful in nature, summer blackberries there just for the picking, it would be remarkable if experiments didn't work. But phenomena are hard to produce in any stable way. That is why I spoke of creating and not merely discovering phenomena. That is a long hard task " (Hacking, 1983: 230).

In fact there are many different tasks in experimenting: designing an experiment that might work, learning how to make the experiment work, and getting to know when the experiment is working. Initially, penicillin "didn't work" very well at combatting infections, and it took twelve years for somebody to make it work. Even then it did not work well because it could not be injected into humans until it was purified, and it was difficult to purify. There were a number of problems that kept it from working. It was destroyed by acid in the stomach. It did not last long enough to destroy the infection in the body unless very large amounts were given, and initially researchers could not make enough. It was expelled from the body in the urine too readily. Some people were allergic to it, and some bacteria were resistant to it. Penicillin did not work until Florey and his colleagues had spent considerable time "creating, producing, refining and stabilizing it."

Scientists have not talked much about action and experiment in science, just as they have not talked about tacit knowledge or solving problems. So an image has developed that experimental work is passive, a case of watching nature rather than interacting with it. In fact, successful scientists make things happen. School laboratory classes should try to recreate some of these features of real science, by letting students try to solve small problems, have real experiences with phenomena, and generally get a feeling for science. But it should not be thought that the students are making any kinds of important or serious discoveries while they are doing this.

Chapter 10

Science, Technology and Society (STS)

Science Technology and Society (STS) is an approach to teaching that focuses mainly on the use of the science curriculum to solve social problems. STS supporters use the term "Scientific literacy" to describe their goals. STS programs are now used to teach biology in Nova Scotia, and goals for this program are copied below from the curriculum guidelines for Nova Scotia.

> "Scientific literacy is a condition which students attain when they master a balance among a variety of indicators. It is attained when a learner:
>
> 1. Recognizes the interactions of the natural, technological and social worlds.
> 2. Communicates scientific ideas clearly through language, mathematics and graphs.
> 3. Appreciates the nature of science.
> 4. Evaluates critically those issues which have a science or technology component.
> 5. Understands the foundation concepts, principles, theories and models of contemporary science.
> 6. Applies scientific processes and concepts to the solving of everyday problems.
> 7. Pursues a life-long interest in the role of science and technology in society" (Curriculum Guide, 118, 1990: 2).

Only one of the seven goals involves subject knowledge and the authors of the curriculum guide point out that they are de-emphasizing content, "not to de-value knowledge but to re-order science education so as to balance the relationship between product, process and context" (Curriculum Guide, 118, 1990: 52). STS programs emphasize social issues and moral development. They characteristically use a distinctive teaching method, problem-based learning (Check, 1992). I will describe and comment on each of these features.

Subject knowledge

Less biological knowledge is taught in grade 12 biology in Nova Scotia in the 1990s than ever before. The authors of the curriculum guide argue that they are still teaching the same amount of science, but their definition of science includes many features other than scientific knowledge, like social issues or process skills. Less than 75% of the time in grade 12 biology, and 35% in grade 10, is spent on subject knowledge, and the rest is spent on other issues and skills. No more actual subject knowledge is taught now than was taught during the progressive era, using the high school textbooks designed around society rather than around the discipline (see Table 4). Even courses in agriculture, taught at the turn of the century, contained as much science as LoRST, and these courses were not taught *as* science courses; they were taught *in addition to* courses that were called science courses. The average amount of a course devoted to non-science subjects over the last century reached its peak between 1910 and 1960, and it was 10% for grade 12 and 25% for grade 10, but it has reached an even higher peak since 1993 in Nova Scotia, where it is 25% for grade 12 and 65% for grade

10 (see Figure 3).

Problem-based learning--the teaching method of STS

STS uses problem-based learning. Instruction begins when a question based on a social issue is posed. Students learn about some aspect of technology to understand the society based problem, then they learn the science needed to understand the technology, this helps them understand the technology well enough to make decisions on a related social issue (Aikenhead, 1992). Since students start with a social problem, and learn the science necessary to solve it, they are learning science only as it fits into the basic structure of a social issue, and only as much as is needed to solve the social problem. So learning science takes lower priority than solving the social problem.

Problem-based learning may be more valuable in adult programs like medicine and business, where mature students can use their extensive background knowledge It is not merely a way of adding problem solving activities to a disciplined-centred course but a method of centering the course on problems (Boud and Feletti, 1991: 14).

The science problem is not there just to provide an interesting context for traditional learning. The students may use traditional means to actually learn the information needed to solve the problem, but problem-based learning forces students to decide for themselves, with guidance from a teacher, which knowledge they need and how they will obtain it. The emphasis in the problem-based process is on *integration* and reinforcement of knowledge rather than developing the knowledge in the first place. It differs from inquiry learning, which expects students to develop the knowledge rather than just finding it and integrating it (Ross, 1991, 36). Problem based learning is more valuable for mature students, especially if they are familiar with the subject they are studying. It is less successful if students are unfamiliar with the subject because they will not have a basis for deciding what knowledge they need.

Social issues.

Probably the most serious criticism of STS is that it leads to a shallow understanding of scientific knowledge, and the organization around social issues contributes to this. STS is designed to teach how science is related to technology and society, and to allow students to make important decisions about societal issues, such as AIDS, drug abuse, cancer, overpopulation, abortion, and pollution (Heath, 1992; West, 1992). This may be a valid goal for education, but it leads to a deficient understanding of biology.

STS can be organized around a social issue (as the current grade 10 biology program is organized around drinking and driving), or it can be organized around biology on a larger scale, but social issues on a smaller scale (as the grade 12 biology program is organized around biological concepts, but includes considerable discussion of social issues). The concepts taught at the beginning of the section on molecular biology in the Nova Scotia grade 12 course include the double stranded nature of DNA, replication of DNA, translation and transcription. While these biological themes are being taught, the following are integrated into the program: "Recognizing the ethical nature of scientific research," "justifying one's ethical perspective," "noting the role of various scientists in the discovery of DNA, "evaluating the role of politics on scientists and their research," "conducting a literature search to research the life and contributions of geneticists such as Dr. D. Suzuki or Dr. K. Ogilvie (Acadia University)," "identifying a minimum of three career possibilities," "stating that the natural rearrangement of genetic material can be artificially replicated through technology and linking scientific issues to social and moral concerns" (Curriculum Guide 118, 1990: 81-85). It is the relative quantity of material in technology, society, and scientific processes and attitudes that makes this distinctively an STS approach, not the order of presenting material. When so much emphasis is placed on social issues, there is a risk that the biology will be lost.

Science has a vertical structure that makes it almost impossible to understand facts picked up here and there. Each concept depends on understanding many other concepts. The network model (described later) sees science as an integrated and coherent body of knowledge. Unless the knowledge is built up in an ordered manner, none of the concepts taught will have any meaning. If an area of science is not taught as an integrated body of knowledge, the resulting knowledge risks being trivial as science, and since it does not lead to a real understanding of the scientific background of the social issue, it may also lead to an incomplete understanding of the social issue itself.

Moral development

Moral development is a new goal for science education. The moral-reasoning ability of students is supposed to be improved through the examination of social issues that involve science or technology. STS emphasizes reasoning on values such as fairness, justice, equality, human dignity and social moral value (Collette and Chiapetta, 1994). Moral issues are taught by presenting students with a moral dilemma (e.g., a story about AIDS) that requires an individual to choose between two approximately equal choices, when each is accompanied by a difficult consequence. Moral education is a distinctive and apparently admirable goal of STS. Not only does it make the relevance of biology clear, it also develops critical thinking by asking students to make decisions in controversial situations. The benefits of such a method are clear, and discussion of social issues can be valuable. However, there is always a risk that this aspect of biology can end up as indoctrination rather than education. This danger is especially strong when the issue seems worthy. The line between education and indoctrination is very fine when important social issues are involved. Unfortunately the people least able to recognize indoctrination are often the people who support a good cause.

An early example of moral education

One issue associated with biology early in the century fits all the criteria for moral education. It had all the features that environmental issues have today; it was based in biology, but had its importance in society. As with environmental issues today, some scientists and science teachers felt then that they had a moral responsibility to educate the public about the issue, and about the dangers to the human species of ignoring it. The people who supported it thought that science had clarified an issue with important social implications, and they wanted only what they believed was good for society. The issue was discussed extensively in biology textbooks from 1920 to 1945, and would have been an obvious candidate for the STS approach if this teaching method had been popular at that time. I will describe it in some detail because it provides a model for some of the issues currently used in STS. This topic was eugenics.

The treatment of eugenics in the first half of the century exemplifies the dangers in applying a few uncertain scientific principles to complex social and biological situations. There are issues today where the risks are similar, and the same kinds of mistakes could be made. What now seems so destructive about eugenics seemed normal, and even positive, then to some people--and there lies the danger. Eugenics also appealed to the worst in human nature, presented a distorted picture of science and misrepresented what was understood by geneticists. It was most popular between 1915 and 1945, when the consequences of its application by the Nazis changed its image.

Eugenics is related to social Darwinism, and is an application of the principles of evolution and genetics to society. Herbert Spencer (1898) began social Darwinism when he applied the theory of natural selection to human society and concluded that nature selects the best and fittest, and gives them rewards. Thus, evolution ensures that the most fit individuals in society are rich and successful, and the least fit are poor and unsuccessful. However, some individuals in Victorian society worried that the poor actually seemed to be more fertile than the rich, and this led to the development of eugenics (Magner, 1994).

Not everybody supported eugenics; in England, many serious scholars questioned the validity of social Darwinism (Stein, 1988). T.H. Huxley, for example, questioned the relevance of Darwin's ideas to politics and ethics. However, social Darwinism did have a strong following in the USA where Justice Oliver Wendell Holmes Jr., a supreme court judge, decided in 1927 that society had the right to use sterilization to keep the unfit from reproducing. A similar law was passed in Canada, and we were still sterilizing individuals without their knowledge as late as 1972. In Germany, eugenics was used by Hitler to justify genocide. Social Darwinism and eugenics fitted into the mechanistic approach to biology, education and society after 1900.

Arguments that were made for eugenics. Supporters of eugenics claimed that education only improves the human race temporarily, because it only affects development not the basic constitution of the individual, and must be repeated generation after generation (Conklin, 1919: 241). However, the human race could be improved permanently by controlling human breeding (Conklin, 1919: 247). Eugenicists planned to keep the "worst types of mankind" from reproducing, and encourage the "best types" to increase and multiply (Conklin, 1919: 275). This was considered necessary because civilization had interfered with natural selection and kept it from improving the human race. Society was preserving the "weak and incompetent," and was allowing the propagation of 'diseased, defective, insane and vicious persons" (Conklin, 1919: 278). The problem was even more serious because there had been:

> "extinction of the world's most gifted lines by enforced celibacy in many religious orders and societies of scholars; by almost continuous wars which have taken the very best blood that was left outside of the monastic orders, by luxury and voluntary sterility; by vice, disease and consequent sterility" (Conklin, 1919:

278).

Eugenics, the solution to this problem, would involve sterilization of "a very small minority of the worst individuals" (Conklin, 1919: 279-280).

There was a wide definition of defectives. The following definition was given in a biology textbook in 1932.

> "By defectives is meant not only the feeble-minded and insane, but criminals, paupers, tramps, beggars, and all persons who are a burden to society. While many of these are confined to prisons, asylums, almshouses and similar institutions, a great many defectives are at large, free to propagate their kind.... The tendency to commit crimes is closely associated with feeble-mindedness, many criminals being mentally defective. The same is true of paupers, drunkards, prostitutes, etc. Mental tests performed on juvenile criminals in state "reformatories" have shown 50 to 90 per cent to be feeble-minded" (Haupt, 1932: 250-251).

Scientists like Conklin and Haupt, quoted above, were overconfident and wrong. They underestimated the complexity of organisms and their genes, and they overestimated the degree to which intelligence, insanity, disease and criminal intent are caused by our genes. They showed the overconfidence that sometimes appears when a new science or technology is developed--a self-assurance that it can be used to cure all social ills. They also allowed their judgment to be compromised, since they ignored the lack of evidence for their views. We could defend their right to speak and write on these issues as citizens, but as George Stein (1988) pointed out, in a paper called *Biological* *science and the roots of Nazism*, it is unethical to misuse your authority as a scientist to have an undue impact on members of the general community. Science can be used, wrongly, to give authority to ideas like racism for a semi-educated public who are confused. Ernst Haeckel (1834-1919) popularized social Darwinism in Germany and Stein describes how this led to an acceptance of Hitler's actions.

The trouble is that scientists like Conklin and Haupt believed they were correct, just as biologists today who campaign on environmental and other social issues believe they are correct. Stein argues that if science should not be used to support racist nationalism, then it should also not be used to support humanitarianism or any other ethical constructs.

> "If it is true that there can be no scientific base for racist policies, must it not be true that there can be no scientific base for advocating nuclear disarmament?" (Stein, 1988: 58).

It is not that well-supported evidence should never be used in discussion of these social issues; it is rather that science should not be extrapolated from areas that are well supported by evidence, to areas that are not, even if, as happened with eugenics, it seems logical to expect them to apply.

Discussion of eugenics in school textbooks. Whether or not it is unethical to use your authority as a scientist to support social causes, it is certainly unethical to do so in school classrooms where students are a captive audience, and the teacher has unusual power and influence over them. Unfortunately the pseudo-scientific view of eugenics appeared widely in school or college textbooks, and probably in as many school classrooms. About one third of the authors, writing textbooks between 1920 and 1945, presented arguments like those given above in favour of eugenics.

Eugenics was discussed in the texts used in Nova Scotia. For example, the following passage is taken from the discussion in *Essentials of Biology* by Meier, Meier and Chaisson (1932), the grade 10 biology text, used from 1934 to 1955 in Nova Scotia:

> "Galton was of the opinion that a person gifted with intellectual ability and having eagerness and power to work could not be restrained. According to this view, the more successful members of society are carriers to hereditary traits higher than the average. It should be noted that in the Saxe-Coburg family there was a tendency for children of high quality to marry other children of high quality and thus keep up the high standard of heritage. Studies have also been made of families having worthless descendants. These descendants are as a rule indolent. Many of them are paupers, vagrants and criminals. Since they intermarry, they continue to cast their dependents upon society. No information in detail will be given here, as it is more pleasing and helpful to study the history of families that make worthy contributions to our citizenship." (Meier, Meier, and Chaisson, 1932: 443 444).

These authors seem to think that traits like: wise ruler, fine mind, literary ability and excellent character can be inherited. Certainly, traits such as indolence, vagrancy, criminality are assumed to be inherited. At the end of the chapter, there are questions for study and discussion, including: "What are some of the mental qualities inherited by man?" and "Make a list of eminent men and women who have come from families of exceptional hereditary traits" (Meier, Meier, and Chaisson, 1932: 445-446).

Those who supported the eugenics movement jumped to conclusions that were wrong and in hindsight they look silly, but they probably did not look so silly then. By 1960 the situation had changed, and human genetics was treated differently in textbooks. By then geneticists recognized that most characteristics are caused by an interaction between heredity and environment, so there is a difference between what an individual inherits and the final phenotypic result. Authors who discussed eugenics thought they were right, and many of them wrote books that were excellent in other ways. They believed they were supporting a worthy cause and were showing students how science could be used to solve serious social problems.

The eugenics movement should be used as a example of how **not** to teach biology, but that lesson has not been learned. Today scientists and teachers are following in the footsteps of eugenicists in discussing environmental and other issues for the same, apparently positive, motives. There is no doubt that ecological issues are important today. But ecology is a difficult subject to study and many aspects of our environment are still poorly understood. In addition, just as the eugenics movement dealt with emotional issues, so environmental topics today are coloured by new ethical and moral considerations. For example, Richard North (1995) demonstrates how environmental issues have taken on a religious value in the 1990s.

"There are several examples of the way many modern people are inclined to discount the evidence of their own eyes or of science when they defend environmental 'victims' from industrial 'villains'" (North, 1995: 39).

He argues, with examples from oil spills and air pollution, how the emotional guilt we feel for "robbing nature of its innocence" has biased the way we approach environmental issues. A culture, called "ecologism" or "green fundamentalism" has grown from ecological insights, and has created ideals that we should live by:

> "we should seek to cooperate more and compete less; we should live within our ecological means; we should live in harmony with nature" (North, 1995: 39).

These are admirable values, and they probably should be supported by all of us, but we should not assume, and teach our students, that all of the environmental issues we hear about are well studied and that the environmentalist point of view is soundly supported by evidence. North points out that ecologism derives from a rather partial reading of ecology and has generated a popular view that nature is fragile, stable and harmonious, while the science of modern ecology sees something quite different:

> "From this perspective, the natural world is seen as having important elements of robustness, flux and tension. Humans are simply a new force in an already dynamic system, and luckily one with at least the potential for intelligent management of its own activities" (North, 1995. 40).

I do not suggest that the new ethical attitudes towards the environment are wrong (I am quite sympathetic toward them); only that these sensitivities make it harder to judge the scientific evidence cooly, and easier to draw conclusions that are not based on valid evidence. It may be valid to propose these ethical considerations but not to suggest that science supports them until the evidence is clear.

The risk of misrepresenting evidence and misusing authority to argue for these causes is stronger in science education than in most disciplines because the culture of science depends so much on authority, and science is so specialized that it is difficult for people who are not experts to judge the truth of what they are told. In addition, there are tendencies of experts in science to overreach their authority.

> "Sometimes people who have knowledge in one area tend to assume that they are *generally* knowledgeable, and are happy to pronounce on matters far removed from their own special area. ...In our own day, scientists have often been singled out for criticism along these same lines. Perhaps the spectacular achievements of science have encouraged the belief that a scientific training can be brought to bear successfully on any question" (Hare, 1993: 43).

There is a tendency for experts in science to believe they have "privileged knowledge". Hare suggests that when experts in science talk with authority in subjects outside their immediate area, "there may be traps which lie waiting in areas beyond his or her expertise" (Hare, 1993: 44). Therefore, we must, as teachers, have "a sense of our limitations" (Hare, 1993: 45). We can still comment on issues, but "in a manner that demonstrates humility" (Hare, 1993: 45).

There are many parallels between eugenics, which suited the mechanistic philosophy of the early twentieth century, and the environmental issues which fit the green fundamentalism of the 1990s. The social problems are different but the methods are the same: application of incomplete biology theory to new situations; followed by authoritative statements to students who think they must accept the word of experts. We assume that an educated public is all that is needed to cure the social ill (just as eugenicists did), and we are so sure we are right (just as they were) that we fail to notice when education shifts into indoctrination. Each biology teacher should consider himself to be at risk of indoctrinating students, and the risk is greatest when we think we are right, because conviction clouds our judgment. An education in biology should not be an indoctrination about good causes. This point was made by Martin in 1926:

> "Whoever is concerned about his education should be on his guard against propaganda. He who assists in the education of another should be doubly cautious. The temptation to convert people to our own particular cause, movement or belief is almost irresistible. An epidemic itch for manipulating the public has infected the whole population" (Martin, 1926: 45).

The recent trend in STS toward moral education, is setting a trap for many teachers. They may fall into indoctrination without realizing it.

Chapter 11

Constructivist Approach

The alternative conceptions movement

In the late 1970s learning theorists began to study how science students make mistakes. One group identified misconceptions (or alternative conceptions) that persisted even after students have studied the correct concepts in school. These learning theorists adopted the "constructivist model of learning" and they developed a variety of suggestions for teaching. The constructivist approach to teaching is currently very popular.

Origins of constructivist ideas

The modern constructivist idea consists of two parts: an explanation of learning as an active model-making process, and an explanation for misconceptions, with prescriptions for overcoming them.

Learning as a model-making process

The alternative conceptions movement adopted the theory of learning by construction. This holds that learning is an active process under the control of the student. Knowledge is not the discovery of some truth that exists "out there," but rather something that is created or constructed by the student to explain her world, her own private model of the world. The function of learning is adaptive; it allows the individual to organize her world, and this means that her models of the world are subject to change; she relates what she is seeing or learning to her existing models. In addition, she tries constantly to compare her models with those of others. This image of learning comes mainly from Piaget who was the first to investigate misconceptions in children, and interpret them in terms of the child's changing theories instead of just seeing them as mistakes (Driver and Bell, 1986; Brook *et al.*, 1989).

The source of misconceptions

The second part of the constructivist theory of learning explains why students sometimes fail to learn; it looks at the obstacles that keep students from abandoning their old theories and adopting new ones. It also describes cognitive exchange--the method by which students can learn. This part of the theory has many sources, but the most recent ones come from analysis of science. The phenomenon was described 40 years ago by Bachelard, a French historian of science, who developed a model of resistance to change that applies both to scientific discovery and to learning. He said that new ideas can only be accepted when a barrier is shattered, and he called this barrier an "epistemological obstacle." The obstacle is any old concept or method that prevents us from accepting a new one. He also used the term, "epistemological break" (rupture) to describe what happens when an obstacle or barrier is shattered, and new conceptions of the world are accepted. Situations have occurred in science that have no equivalents in common sense experiences, or are incompatible with other theories. These breaks bring radically new conceptions of nature (Gutting, 1990). The idea was developed further by

Kuhn (1970) in his theory of scientific revolution. Kuhn described how scientists resist change. They accept new models or paradigms only when evidence accumulates that does not support their original paradigm, and an internal conflict develops.

Members of the alternative conceptions movement adopted this theory of scientific revolution as a model to explain why students find it difficult to replace their misconceptions with acceptable school knowledge. They said that students keep their old models for exactly the same reason scientists retain their old paradigms, because the beliefs associated with them interfere with the adoption of the new model (Hewson, 1985; Pines, 1985). The second part of this learning theory, explaining how to overcome obstacles and facilitate learning, is also based on the model of scientific discovery. The teaching methods that have developed from it try to imitate the process scientists go through during discovery (Posner *et al.*, 198_; Strike and Posner, 1985).

Model of scientific revolutions. Kuhn said that discovery or learning is a new insight into nature that occurs because an individual learns to look at a phenomenon in a new way. It begins with an anomaly. The scientist begins with an expectation, and nature fails to conform to that expectation in some way. Awareness of the anomaly begins the discovery process; it is followed by a period in which the scientist observes, experiments with, and thinks about the anomaly, trying to explain it. In this process he revises his expectations and modifies his methods. As the process continues, the discovery usually makes an impact on other theories so it "leads to a change in vision" (Kuhn 1977: 175). Kuhn used a detailed example to bring out some features of this kind of learning. Before

Galileo, there were not separate concepts of instantaneous speed and average speed. Galileo introduced the idea of instantaneous speed by describing situations in which one body moves faster than another at one instant but covers a larger distance more slowly. With these situations, Galileo uncovered a contradiction that had been just under the surface for many people. The older concept that only included average speed, was not wrong, just incomplete. A problem developed only on the rare occasions when the two kinds of speed existed in a contradictory fashion. As experiences of this conflict accumulated, people were vaguely aware that something was wrong, but they did not know what. The contradiction in their thought could not be eliminated until it was recognized. Galileo didn't actually find new evidence, but described old evidence in a way that showed the anomaly more clearly. Since this evidence had not been completely assimilated, there was a misfit between past theory and past experience; Galileo's description disclosed the misfit (Kuhn, 1977).

The theory of conceptual change. The ideas described above for scientific discovery have been used by the alternative conceptions movement to form a theory of learning called conceptual change. Members of the movement have suggested that there are two sources of knowledge for students: the informal knowledge they gain from everyday life and the formal knowledge learned in school. Before formal study, persons have explanations for scientific phenomena that are different from those in the science they learn at school. New school knowledge interacts with everyday knowledge during learning and everyday knowledge can be either a bridge to new learning or an obstacle

(Pines and West, 1986). If the two forms of knowledge (everyday and formal) complement each other, the models formed from everyday knowledge assist in the assimilation of new information and learning is easy. If the formal knowledge is abstract and the student has little previous experience with it (for example in studies about molecular biology), then the student has few previous conceptions, and there is little interaction between old and new knowledge. Learning will be difficult because the student has little to tie the new knowledge to, but there will be no inhibition of learning. Learning in these first two cases is called *conceptual development* (Pines and West, 1986). A third possibility is that the learner's existing model conflicts with the new knowledge introduced by the teacher. Then there can be a conflict between the student's old beliefs and the new concepts presented by the teacher. The student may not even be aware of this conflict, but the old beliefs will still make it difficult for him to accept the new concepts. He will learn only by abandoning the old model and accepting the new knowledge in its place, but this is hard to do. The kind of learning in which students abandon misconceptions is called *conceptual exchange* (Champagne *et al.*, 1985; Strike and Posner, 1985).

Consequences for teaching. As a result of the constructivist theory of learning, several recommendations for teaching have been made. Teachers are encouraged to find out what the students know about a subject before beginning to teach it, use Socratic questioning to force students to clarify their own opinions, introduce discrepant events to help students focus on the conflict between their model of the subject and the scientifically accepted model, and give students a choice of theories in each subject so they can weigh the evidence and make their own decisions rather than accepting a "right" answer (Driver 1989).

In addition to these general recommendations, a specific teaching method has been developed that is sometimes called the **cognitive conflict method** or **constructivist approach**. Pines and West (1986) describe its features below:

"(a) **The awareness phase**. The student actively seeks to integrate new information into his existing framework and finds that his existing belief system is unsatisfactory. Teachers diagnose errors, then provide a range of activities, followed by class discussion, designed to bring out and highlight competing points of view."

"(b) **The disequilibrium phase**. The teacher introduces anomalies (discrepant events) that challenge existing beliefs. The teacher needs to adopt an adversary role--a devil's advocate or Socratic tutor."

"(c) **The reformulation phase**. The teacher presents formal scientific concepts that lead to the resolution of anomalies. This dissipates the cognitive dissonance that has been produced. The students will be uncomfortable with the discrepancies between their existing belief systems and the anomalous events observed that they will eagerly accept the formal theories being offered as their own" (Pines and West, 1986: 594).

Evaluation of the Constructivist Approach.

The constructivist model of learning has benefitted teaching. Just as inquiry learning emphasized the need to push students to think, so the constructivist approach has taught us to see the students differently. But even if this model does describe accurately how students learn, that does not mean that we should use the teaching methods recommended. As Millar (1989b) pointed out, the constructivist model of learning probably describes what we all do when we learn and it need not be taught. It is a good idea to find out what the students know before teaching them. Socratic questioning is also fine, as long as students know enough about the subject to be able to describe their concepts. However, the two most important teaching recommendations, creating cognitive conflict by demonstrating anomalies, and giving students a choice of theories and allowing them to chose for themselves, are hard to accomplish in science classrooms.

Problems with cognitive conflict as a teaching method

The theory of conceptual exchange was developed to explain misconceptions that had already been identified. Therefore, the constructivist theory of learning is slanted toward one kind of learning, conceptual exchange. It is reasonable that this teaching method should be developed to cope with the conflict situation; it deals with a problem that requires a solution. However, There are a number of reasons why cognitive conflict cannot be used all the time, or even much of the time, in science classes. It should not be seen as a universal teaching method.

Too much emphasis on conceptual exchange. It is the overemphasis on conceptual exchange that most weakens the constructivist theory of learning and the constructivist teaching methods that have emerged from it. Since constructivist models of learning and teaching were developed to explain misconceptions, this may have led researchers to overemphasize the mistakes people make, and pay insufficient attention to the concepts that students learn in a straightforward way. Conflict occurs relatively rarely in science; the same few misconceptions are discussed over and over by researchers. Therefore this method may not be suitable for most teaching. It should be reserved for appropriate situations.

Cognitive conflict as a teaching method. Anomalies are not likely to be effective in teaching unless the learner is already familiar with the topic, and is already aware of discrepancies that cannot be accounted for. Science is so removed from the everyday experience of students that they rarely become familiar enough with the subject to be able to recognize an anomaly when it occurs. Since each student's experience is unique, it is hard to create this recognition in a classroom setting. This teaching method was introduced because it recreates a type of scientific discovery, but there are fundamental differences between scientists and students. Scientists are very familiar with the subjects they work with while students are not. An anomaly that may be obvious to a scientist would not be visible at all to the student.

Anomalies in scientific research. In science an anomaly exists between what is expected and what is observed. However, as Kuhn (1977) points out, this is really an anomaly that exists within the mind of the scientist--the anomaly is knowledge he is aware of that makes him uncomfortable, or knowledge on the periphery of his mind that he has not yet assimilated into the centre of his theories. It causes the scientist to notice a discrepancy he had not noticed before. Skill and knowledge are required to recognize an anomaly.

> "To say that an unexpected discovery begins only when something goes wrong is to say that it begins only when scientists know well both how their instruments and how nature should behave." (Kuhn 1977, 174)

If the scientist or student (who has all the knowledge available that he needs in the background), is confronted with the conflict, he may be able to recast his concepts. However, this only works if he already has the knowledge he needs and is uneasy with it. As Kuhn says:

> "In fact the conflict that confronts the scientist must be one that, however unclearly seen, has confronted him before. Unless he has already had that much experience, he is not yet prepared to learn from thought experiments alone" (Kuhn, 1977: 61).

Learning cannot occur unless two features exist: first the basis of learning must already be present in the mind of the individual student -the contradiction must already exist *in the mind of the student* (not in the mind of the teacher); and second the contradiction must be recognized *by that student*.

It should be clear that using anomalies in teaching will work better when students are very familiar with the subject, when they are comfortable with the knowledge and have already assimilated it. Then the use of anomalies will allow students to clarify issues for themselves. However, anomalies cannot be used effectively when the subject is being presented for the first time. The teacher cannot present anomalies and hope the students will see them, nor can she create conflict between two theories unless the students are sufficiently familiar with both theories.

Motivation. The cognitive conflict method does not necessarily motivate students and it can decrease their interest if not handled very carefully. Dreyfus *et al.* (1990) found that bright students enjoyed cognitive conflict but unsuccessful students do not like it; some are just indifferent to conflicts created and others are threatened by them.

A variety of misconceptions - a variety of solutions. There are different causes for the misconceptions, and each cause needs its own solution. Cognitive conflict methods are likely to help eliminate certain misconceptions but not others. When you analyse the reasons for the mistakes people make in science, they fall roughly into categories. Here are my interpretations of the categories.

1. The tendency to think in one-dimensional terms. Mistakes are made because students view things in simple one-dimensional terms while scientific subjects are multidimensional. For example, Driver *et al.* (1985) reported that students tend to reason only from what they can actually see in a situation. Therefore they tend to think that a solute like sugar disappears when it dissolves, and do not take it into account when answering a question about solutions. Or they treat light as though it does not exist, unless they see it as a patch of light on a surface. In addition, they interpret phenomena in terms of absolute properties rather than as an interaction between the elements of a system. In explaining the action of a straw or syringe, many pupils considered only what was happening in the inside, attributing the motion of liquid in the straw to the power of suction, rather than thinking of it as the result of pressure differences between the outside and inside. Similarly, they tend to focus on things that are changing and ignore equilibrium states. For example, they acknowledge that a force is acting on something that is moving, but don't accept that a force can be acting on something when it is still.

It is hard to understand a complex, multi-dimensional, abstract subject because it is hard to take into account so many issues (some of them invisible) at the same time. This makes some concepts in science difficult for anybody to learn. Some of these concepts will probably always be misunderstood by the majority of the population no matter how they are taught. Some strategies associated with constructivist approaches will probably help somewhat. Essentially anything that gives students enough practice and increases familiarity is likely to be helpful, and cognitive conflict is one of several methods that may be useful.

2. Misunderstandings associated with language. Many misconceptions are caused by confusions over language. Words such as heat, power, rate and sexual reproduction, have meanings in the everyday world that may be slightly different from their meanings in science. Therefore, students fail to identify the correct meaning in science classes. Constructivist methods should be effective in these cases, but so should other methods that clarify meaning.

3. Teacher-induced misconceptions. Most misconceptions are created unintentionally by teachers, often in trying to simplify explanations. For example, high school genetics teachers may introduce students to Punnett squares but not explain why they are used, so students assume they should be used in all genetics problems, even where genes are linked. Teacher induced misconceptions can be eliminated by identifying these misunderstandings and explaining the differences clearly. No special teaching method is needed.

4. Misconceptions that will probably never disappear. Some misconceptions should be corrected, but many will probably never disappear. Some concepts are incorrect from the point of view of the scientist, but are useful to non-scientists because they allow them to explain phenomena they could not otherwise understand. Some misconceptions can be resolved at only advanced levels of training because the necessary background is not available until that point (Dreyfus *et al.*, 1990). In these cases there seems to be no point in creating cognitive conflict to make students dissatisfied with their own explanations unless they can be given enough information to understand the correct explanations. The structure and functioning of the cell membrane falls into this category. Dreyfus *et al.* suggest that a subject like this is often taught at a level that is too difficult for the students. As a result, they are incapable of understanding the correct concept given their level of knowledge, so they develop for themselves a "satisfactory" but scientifically wrong explanation that fills the vacuum. If a conflict is created, students become dissatisfied with their own theories and recognize they need better ones, but at their level of scientific understanding, they are not able to construct satisfactory concepts, so they construct explanations that are not very different from their old ones. Some of these misconceptions should be accepted and ignored. Emphasizing them is putting priorities in the wrong place.

Choosing between theories--misrepresenting science

Should we, as constructivists suggest, give students a variety of theories, and the evidence supporting them, and allow them to make their own decisions? Most of the time this approach will not work in science classes because it is not compatible with science as it is done by scientists. It sounds ideal that students should be given more than one theory about a topic, along with the supporting evidence. They are allowed to make their own decisions about which theory is correct, on the assumption that the evidence will be so persuasive that they will come to the correct conclusions. To explain why this apparently powerful method misrepresents science, I will describe in some detail how decisions of this kind- about which theory is correct are made by scientists.

The Social Structure of the Scientific Community

The image of science, as an individual activity in which each scientist is independent and makes his own decisions, has caused educators to underestimate the social structure of the scientific community. The success of science depends not just on individual scientists, but in a large measure on the way the scientific community collects and distributes knowledge (Barnes, 1985). Specifically, the knowledge of each individual builds on the knowledge of others because the social structure has encouraged specialization, an intellectual division of labour, and an interdependence among scientists. Furthermore, there is much collective judgement--in the refereeing of scientific papers and the dispensation of money for research--of the worthiness of the individual scientists and their science.

Our society values individualism so we have been slow to understand and accept this communal and authoritarian structure of science--the very ingredients that make it so successful. This means that some of the features that make science most effective are the same ones that other members of our society, especially educators, dislike the most and would like to change.

How decisions are made in science. Within science, decisions on the validity of a theory are made only by scientists actively involved in research in that area. Scientists who are further removed from the research accept those decisions without question. We could identify levels of proximity to the decisions. The first level contains the individual working scientist, who makes his own decisions about specific research problems. The second level contains a small group of individual scientists, collaborating on research and publishing joint papers. One individual scientist may collaborate with others (students and colleagues) on research. The third level of organization is a somewhat larger group of scientists, usually from around the world, who work so closely on a topic that they follow each other's work in the literature and correspond with each other. Members of this group essentially make the decisions about what to accept or reject in the small area of science that concerns them. Then there is the larger group (fourth level) of scientists who, while each working on different subdisciplines (like mapping chromosomes), could be classified as working in the same topic (e.g., genetics). They are familiar, at a general level, with the research in each of the other subdisciplines of the topic, but they are not familiar with the details. The fifth level would be all biologists and the sixth level would be all scientists.

It is important to distinguish these levels because behavior differs depending on the level. The group of scientists who make up the second and third levels make the real decisions about which theories to accept within their small areas of research. These scientists commonly check each other's work and correct each other's mistakes as a normal and acceptable practice. All individual scientists make their own decisions; nobody tells them what to believe. However, they will be forced, by evidence on one side, and by the beliefs of the rest of the group on the other, to bring their beliefs into line. A story is told about Oswald Avery and DNA that shows how even a senior scientist, if he makes the wrong decision, will be corrected by other scientists (Judson, 1979). In 1928 the microbiologist Fredrick Griffith discovered that DNA was the "transforming principle" (or genetic material). He showed that a living, benign strain of bacteria, injected into a host animal simultaneously with a nonliving virulent strain, will become actively virulent. When Griffith published these results, other scientists were surprised, and Oswald Avery, a prominent scientist in this field, did not believe the results. He was not even willing to try the experiment himself. However, the junior scientists working in Avery's laboratory were uncomfortable with this response, so they repeated the work while Avery was away and confirmed Griffith's results. When they showed their results to Avery, he changed his mind.

This example illustrates that individuals who work within the same area of research influence one another, not because they do as they are told, but because they recheck each other's work. Scientists intimately involved in an area of research usually reach a consensus, and agree on theories because they assume that there can be only one answer. They are not forced to agree with each other, but individuals who cannot persuade others, or are not persuaded themselves are simply ignored. Scientists do not choose this course; it is forced upon them by the nature of their work. Since knowledge produced by one scientist can be used as the starting point for others, each scientist wants to know he can depend on it. Each scientist is affected by the quality of the knowledge, because each must use it as a stepping stone in his own research. Every scientist benefits if this joint control of knowledge is successful, so every member is willing to help others, exchange information and materials, and collaborate to improve the final product.

A hierarchy is built up within the decision-making group of researchers based on credibility. A scientist who receives recognition for successful research has more influence on other scientists. They trust his word in the future because of the good work he has done in the past. Credibility is more than just recognition; it defines how much others can trust your ability and judgment (Latour, 1987). Each scientist bases his work on the word of others. He must know whose word is dependable, or his own work will suffer. Scientists stake their careers on credibility, so they quickly learn who does careful work, who is dependable and who is usually right. It was a sign of Florey's credibility that he was able to persuade the Americans to take the risk of producing penicillin.

> "Florey and Heatley went to USA to persuade them to begin production of penicillin. ... In the end the decision to begin production was made by A.N Richards with whom Florey had worked in 1926 when he was in America for a year. He had a deep respect for Florey and for his integrity as a scientist. It was this respect that decided him to accept Florey's judgement of the potential value of penicillin, rather than the somewhat scanty case records he could produce Richards was influential and approached drug companies, offering support by the American government" (Macfarlane, 1979, 341).

It is fundamental to the communal approach to knowledge that each scientist in a subdiscipline is willing to judge the work of others, and allows others to correct his mistakes. This is the real source of the success of the system. It makes the community of scientists more effective than they would be as individuals. As Barnes points out, it is this checking that tends to eliminate mistakes and makes the information believable. Individual scientists are error prone and unreliable at times, just like everybody else, but with many individuals, each capable of making errors, but each repeating and rechecking the work of others, there is a tendency for errors to disappear, and the collective result is much more accurate (Barnes, 1985: 42)

Not only are scientists willing to accept a common theory or "right" answer to each problem, but they *need* a single answer, so they can build future work on it. The point at which they accept a theory or fact is called *closure*. Kuhn (1970) argued that it is this willingness to agree on a single answer (paradigm) that distinguishes science from other disciplines. When there is no agreement, there is no progress, because each person must argue each issue from scratch. Agreement on a paradigm gives each scientist confidence to concentrate on small issues and solve small problems--and this is the source of progress in science.

When scientists are more removed from a certain area of research (at the fourth level or above), they accept, without question, the word of those working actively in the field. Scientists are so specialized that they are able to properly judge only the theories that lie within their small area of expertise. This establishes a hierarchy within science in which, for each issue, the opinions of some are valued more than the opinions of others. Although it creates an authoritarian aspect to science, the specialist hierarchy allows scientists to accept knowledge in areas outside their area of expertise without questioning it. They do not, as constructivist educators ask of their students, question every theory for themselves, examine the evidence, and make their own decision.

Judgment in science and science education. If we were to follow the advice of constructivist educators, we would give each student a choice of theories in each topic and the evidence needed to judge them. Each student would be allowed to make her own decision about what to accept and what to reject. This sounds ideal in educational terms, but it is not realistic in terms of science. Because science is specialized and scientists learn to trust the word of experts, those in science education who think that students, with no background knowledge, will be able to judge every theory for themselves seem to have an erroneous view of science. Scientists do not expect to judge each theory for themselves, and they would expect students in classrooms to behave similarly. If scientists think they do not have enough information to judge results outside their own speciality, they are willing to accept the word of experts. Should not students in classrooms be able to do the same?

On practical grounds. There is a very practical reason why it can be hard in science to give students the evidence supporting two scientific theories to allow them to make judgments. Often there are *not* two competing theories (e.g., of protein structure), and *never* were. In most cases the theories that have been proposed to explain a phenomenon, existed in different historical times, or in different contexts, so they cannot be compared on equal terms. To provide alternatives we would be obliged to concoct false theories, or evidence, and create unnatural situations in which students would make the kinds of choices never made by scientists.

In addition, there are practical grounds for not presenting the evidence that supports theory. It is not easy in science to present evidence in a clear and simple way. For example, the evidence supporting DNA as the genetic material is complex, detailed and cannot be understood properly without an extensive biological background. As I tried to show earlier in my description of how the treatment of science changes with time, biology books do often present evidence for theories that are new and these are among the most difficult passages to understand in these texts. Such descriptions of evidence are gradually left out of discussions of these topics, and the later explanations are easier to follow. It is ideal, in theory, to ensure that students always have the evidence they need, if not to evaluate scientific theories, at least to see that they are supported, but it will always make the subject even more complicated and difficult to follow than it already is.

An issue of honesty. The evidence used originally to make decisions about theories is usually too sophisticated for students to properly understand, so situations created to make them think they are making their own decisions are often artificial. It is detrimental to allow students to **think** these decisions can be made on superficial grounds (Hodson, 1988b).

Recreating the sense of making scientific decisions. Science operates on a one-way time line, and because scientists assume there is a single answer, the one supported by the evidence, it is difficult to recreate the situation that existed before that answer was known. Knowing certain information changes the world irreversibly. We can pretend in science education to reverse the effects of time, but unless we are openly teaching the history of science, the exercise will always be false and ineffective. Students value honesty in their teachers, and there are few situations in which the kinds of theories and evidence wanted by educators actually exist.

The importance of scientific knowledge

It is the knowledge of science that is important, rather than the particular methods used by individual scientists to gather it. Scientific knowledge goes through many processes: It is developed by individuals as small units like facts. Then these smaller units are integrated into the overall structure of scientific knowledge. But it does not stop there. Knowledge, once produced and integrated into the framework is not, as some educators have suggested, just the "products" of science, of no real value or interest once produced. It is also not just another theory, proposed by an academic, and available for consideration by others. Instead, this knowledge is worked and reworked by the scientific community; it is seen in a new perspective as new facts and theories appear, and it changes as new relationships emerge. The rapid progress of science occurs because scientific knowledge is built on other knowledge. The network model of scientific knowledge proposed by Mary Hesse (1974, 1980) allows us to visualize what happens to knowledge as it is accumulated.

Network model of knowledge. Hesse (1974, 1980) compares knowledge to a web or network of concepts. The concepts are found at the "knots" or intersections of the web, and the relationships between concepts are the strands in the web that connect concepts to each other. All concepts are related to each other, so you can only understand one if you have some understanding of those around it. If a new theory is proposed, it must satisfy the evidence, but it must also be consistent with the rest of the network of knowledge. New concepts are added, and new relationships are continually made, so the network is active and constantly changing. This kind of view of knowledge is not unique to science. A similar image of knowledge was described by White (1967).

Hesse (1974) developed the network model of knowledge to explain the paradox that no single fact or theory directly corresponds with truth, and yet scientific knowledge is generally true and has some correspondence with reality. Theories, which would be undependable if they had to stand on their own, are bound together in a network which ties them to all existing knowledge. Knowledge becomes stable, not just because it is supported by evidence, but also because it is coherent with other knowledge and with past evidence. Most evidence will be true, but some will not, and we never know for sure which evidence will be wrong. Thus we judge whether to believe a theory, not just by looking at the particular evidence, but also by testing how coherent this theory is with the rest of the knowledge in the network. For example, when penicillin was first found, its ability to kill bacteria while remaining non-toxic to humans was ignored because other chemicals had not been found that could do the same thing (i.e., it was not coherent with what was known at the time). However, after sulpha drugs were found, penicillin fitted differently into the picture; its properties were now coherent with what was known to be possible, and it was actively pursued.

Sometimes new theories are not accepted by the scientific community even when they appear to be supported by evidence. To outsiders, it appears that scientists are refusing to be open minded, but these scientists may simply be judging whether the knowledge is coherent with other knowledge. This is what happened in the early 1980s when the theory that water has a "memory" of substances previously dissolved in it was not accepted by the scientific community because the evidence was not coherent with existing knowledge. It contradicted theories on the structure of water, which were themselves well supported by evidence.

Not all knowledge is equally well accepted within the scientific community, so Lakatos (1970) proposed a model in which some theories (called research programs) are more stable than others. His model can be visualized as a series of three circles one inside the other. The inner circle contains the theories strongly believed to be true. These are unlikely to be changed even when evidence seems to contradict them. They take some of the uncertainty out of science, by giving scientists some knowledge that they can take for granted. Examples are the Darwinian theory of evolution and the structure and function of DNA. Surrounding this inner core is a "protective belt" of "less essential theoretical positions" which could be changed given enough evidence. On the outside are theories which are not very firmly supported and are modifiable. Hesse and Lakatos both believed that theories could not be assessed in isolation, and they both suggested that the network of knowledge makes scientific revolutions unlikely (Hesse, 1980; Duschl, 1990).

Latour (1987) suggested that the scientific community is most effective at accumulating "local knowledge" in a way that makes it universal, and this creates a "great divide" between scientific knowledge, which builds on itself, and knowledge in other disciplines, where knowledge remains local. The accumulation of local knowledge into a knowledge network, agreed upon by a group of scientists, allows theories, ideas and facts to be placed in juxtaposition, and seen in a new light. This process of integrating knowledge, restructuring existing relationships, putting theories together that were previously separate, and reorganizing the fabric of knowledge leads to the creation of new knowledge. Delbruck acknowledged this process while accepting the Nobel prize.

> "While the artist's communication is linked forever with its original form, that of the scientist's is modified, amplified, fused with the ideas and results of others, and melts into the stream of knowledge and ideas which forms our culture" (Delbruck, 1969 while accepting the Nobel prize, Quoted by Judson, 1979: 614).

Implications of the network model for education. The most immediate implication of the network model for teaching is that STS courses that are not organized around the discipline will have difficulty teaching disciplinary knowledge properly. Since scientific concepts build on each other, it is often impossible to understand certain concepts without understanding those on which they are built, or are related to. It is not possible to move to an isolated concept, use it and move away again. Concepts in science have very little meaning in isolation. Instead, science should be taught as part of the larger fabric of knowledge. This means that it should be taught in a large enough chunk of knowledge to be understandable. The following example illustrates this. In the textbook, LoRST used in the current grade 10 integrated science program, students learn how alcohol moves in the blood to the lungs. There it diffuses from the capillaries into the alveolus.

> "Through your micro sub window, you observe that only a tiny fraction (2%) of the ethanol molecules actually diffuses through the capillary walls into an alveolus. (Remember, one "alveolus," two "alveoli.") The actual amount of ethanol escaping depends, of course on the concentration of ethanol in the blood.

For instance, a 2% escape from a 80 mg/mL mixture is twice as much ethanol as a 2% escape from a 40 mg/mL mixture. In other words, twice as much ethanol will diffuse out of a 80 mg/mL solution than out of a 40 mg/ml solution (Henry's Law)" (Aikenhead, 1991: 211).

This description of the movement of alcohol into the alveolus is important to explain how a breathalyser works. However this is the only information given about lungs and their operation. Students are not told how lungs work, how oxygen is transported into capillaries, etc., so they have no way of comparing this explanation about the behavior of alcohol in the lungs with any peripheral knowledge and may understand this topic poorly.

Can students make valid decisions about scientific issues? Science is different from many other subjects taught in school because it is more abstract; students also know few of the details and have little background knowledge. It may be reasonable in subjects like social studies to ask students to evaluate evidence and judge theory, because they have a background of general knowledge that they can use in their decisions. In other words--they have the peripheral knowledge needed to understand the central concepts properly. In science however, even if the concepts and evidence supporting them could be described in a simple enough way, and they usually cannot, students do not generally have any background or peripheral knowledge, so they are fundamentally different from scientists, and their judgments will be made blindly. The network model of knowledge shows why science students cannot readily judge scientific theory for themselves. No concept can be studied or evaluated in isolation. It must be judged on the basis of the whole fabric of existing knowledge. Individual scientific theories cannot be evaluated without reference to other connected theories.

As a partial solution to the problem of allowing students to feel in control of their learning, and yet not misrepresent science, Duschl (1990) proposed a teaching model with a structure like the Lakatos model above. Students would be encouraged to learn, and accept, some theories (the hard core ones) without question, but would also be introduced to other, less firmly-held, theories and encouraged to make judgments. There are still problems with this, and a better solution would be to ask students to solve problems that use these theories, rather than asking them to make judgments about the theories themselves. Circumstances can be found in which students use important concepts to explore particular situations. This allows them to make decisions without the pretence of deciding important issues.

Students should not be led to think they are making valid decisions for themselves, and given the impression that scientific knowledge is based on single pieces of evidence. The following example from *LoRST*, (the grade 10 textbook) gives this incorrect view of science. The author describes a surprising result from one study and says that scientists have not yet decided whether it is true. Then he tells students that they will be given the results and will be able to make their own decisions. No other knowledge is given.

> "Recently scientists were surprised to discover that some ethanol can be destroyed (chemically changed into something else) in the stomach. Up until 1990,

scientists thought that *all* alcohol consumed by a person diffused into the bloodstream. But apparently this is not necessarily true. This new evidence, however, is based on just one experiment. At the present time, scientists have not reached a final consensus (you'll get a chance to decide for yourself because the experiment is the topic of Activity 3.1). The results are **tentative** -open to change in the future. All scientific knowledge is tentative" (Aikenhead, 1991:203).

Students are expected to learn from this passage that all scientific knowledge is tentative, but this creates a false impression; it is not so tentative that any child can come along, with no knowledge about the subject and only one piece of evidence, and make valid decisions about it.

Chapter 12

The Elusive Traditional Method

Nobody lays claim to the traditional teaching method. It is a name imposed, from outside, on those who do not wholeheartedly support new teaching approaches. Nevertheless, common features of traditional methods can be identified. By traditional, I refer to the structure in which content is presented first, and activities and problems follow. The subject is usually explained logically, and subject knowledge is emphasized. Traditional teachers are realists about scientific knowledge. The lesson can have this traditional structure, and yet be designed to serve the interests of the students. The traditional structure can be used in a lesson which is interesting, contains good examples and activities, and includes extensive questioning and class discussion. Many traditional teachers are up to date in their subject and interested in the welfare of their students. There are good teachers and poorer teachers in this group, as there are in any others.

I have identified many faults of the modern teaching approaches, but the traditional approach has just as many faults. For example, it does not present the first exciting, stages of frontier science. The traditional approach, when used in its pure form, is just as unrepresentative of science as are the other teaching methods in their pure forms. Pretending that scientific knowledge is always true is no more honest than pretending that it is always tentative; emphasizing scientific knowledge at the expense of method is no better than the opposite. Similarly, it is no better to give students the idea that there is no freedom or open-endedness in science than it is to give the impression that science is totally open and accessible. The answer must lie somewhere in the middle. I believe most teachers are really in the middle themselves. They want to take the needs and interests of their students into consideration, but they dislike or distrust some aspects of modern curricula and teaching methods. They want to take some account of the discipline, but they recognize the distinctive problems associated with teaching science, and believe they can ameliorate these features by making compromises.

A Composite teaching method

Learning, like science, is too complex to be described by one theory. It is not an instant phenomenon; but a process that occurs over time. Once a concept is introduced the individual takes time to become familiar with it, then assimilates it into his or her conceptual framework, and only then can he reorganize it and apply it to new situations, or use it to solve problems. Learning, then, has a number of stages, each with its own characteristics: for each stage a different teaching method has its advantages.

Stages of development within science. If learning is a composite process, then there is no universal teaching method. For example, the constructivist method will be useful only after students have considerable background knowledge in a subject because this method helps in the reorganization of knowledge and the replacement of concepts. Within one science course a student might be at different stages of learning for different concepts. A student may already be familiar with genetics so the constructivist teaching method is suitable, but if she has no prior background in cell respiration, this method is unsuitable.

Differences between disciplines. Students may also be at different stages of learning in different disciplines. For example, the constructivist method might be suitable for introducing subjects like English, psychology, and history which use everyday language and depend on background assumptions found in everyday life (like some understanding of human nature). Students may be able to skip the earlier stages of learning in these disciplines because of their background knowledge. However, science is abstract and uses its own language. Unfamiliarity (a lack of background knowledge) distinguishes science students from those in other disciplines. Science students have to first learn the new language, as well as the kind and quantity of knowledge in science that would be considered background in other disciplines.

Discussion at the early stages of learning may also be useful in subjects like history because students **think** they have enough background knowledge to make judgements, when in fact they don't (this is one of the problems of using everyday language in a discipline). In that case, discussion serves the function of clarifying just what is meant within the discipline, and removing the incorrect assumptions early. In the early stages, science students neither **have,** nor **think they have**, any real background knowledge, and they need some opportunity to become familiar with a subject before being asked to discuss concepts and give opinions.

If the need for familiarity (background knowledge) is one of the features that most distinguishes science from other disciplines, then teaching methods appropriate for some disciplines may not be appropriate for science, at least not at the same stages. Methods appropriate for other disciplines in the early stages may be appropriate for science only at later stages of learning. Below is a brief example of how teaching methods can be tailored to suit familiarity and stage in the learning process.

When a concept is new to students and they do not have a fully formed image of it, they are able only to listen and try to memorize it; they are not yet able to integrate it fully into their framework of knowledge, talk about it or manipulate it. Often when students first encounter a new, abstract subject like population ecology with its graphs and equations, they appear to follow the explanation and find it interesting, and yet are not able to use it to solve a problem, or even to explain it on a test. At this point they simply need a chance to become more familiar with it. They could accomplish this by doing further reading, trying to solve simple problems or carrying out laboratory work, one of the major functions of which is to increase familiarity. At this stage, traditional teaching is appropriate. No useful purpose can be served by asking students to discover such foreign concepts for themselves, or guess at answers about subjects beyond their experience.

As familiarity increases, students may be able to express the concept in words, and use it to answer simple questions. At this point they should be pushed to stretch themselves further. They should be given a series of problems or exercises that ask them to apply the concept, and they should be given short tests and assignments that ask them to review it, and put it into their own words. Inquiry methods, problem-based learning or problem-solving methods are appropriate at this stage. It could be argued that the idea of inquiry is impossible when the concepts have already been given, but inquiry should be used, not to learn the central concepts in a discipline, but to discover peripheral aspects of the topic. This keeps the foundations solid, and gives students an opportunity to develop them. Inquiry methods are best suited to pushing students beyond their starting knowledge. Only then will they be able to reorganize and clarify it. After this, a method like the constructivist strategy can be used. The constructivist teaching strategy requires that a student be so familiar with a topic that he can recognize an anomaly. Science students, most of the time, are not yet at this stage.

Discussion is useful at all stages, but it will serve different functions, and should be carried out differently, at different stages. At the beginning, discussion helps students become familiar with the concepts and understand the words better. The real function of lectures at this stage is to increase familiarity by describing the concepts in a way that differs from written versions. At this early stage, students have considerable difficulty discussing the topic themselves (even in remembering the words to use), so they avoid discussion rather than risk losing self esteem. Later, discussion will allow students to gain confidence, as they rearrange their knowledge and form their own concepts.

A composite model for science education suggests that science students should be given a variety of assignments (or opportunities), some to increase their familiarity, some to apply their knowledge and finally, some to restructure and clarify their knowledge. The major teaching methods fit into this model.

SECTION 4

REPRESENTING SCIENCE

Science is hard to teach because it is hard to understand. Not only is the subject matter difficult, but science as an activity is also hard to understand. I will explore the causes for this. The problems are not something we can solve easily, nor are they anybody's fault; they are built into the discipline. Sociologists of science have identified areas where misunderstandings occur, but often they have observed the problem, then misinterpreted what they have seen. Unfortunately, many experts in education have accepted these explanations without question, so they now convey a picture of science that is accepted by sociologists of science, but not by scientists themselves.

I will describe some sources of misunderstanding about science identified by sociologists, and then give my explanations for them. Some sociologists say that scientists "misrepresent" their activities in research papers; they say that scientists do one thing and say they do another. Others have described how attitudes of scientists seem to change toward knowledge as time goes on. I will also discuss reconstruction (the process of constantly reworking and reconstructing knowledge) that permeates every activity of science, but is almost completely ignored. It was common in the past to teach students that scientific theories are true, and now it is more usual to tell them that scientific knowledge is tentative. I will define truth as it applies to scientific knowledge.

It is important to emphasize that the real significance of these issues is not how they reflect on the truthfulness of scientists, or the dependability of scientific knowledge.

They are important because they bring out one of the most important issues for education the difficulty in representing science properly. It is hard to know what is actually happening in science; it is also hard to understand what scientists think science really is. It is even harder to decide how science can be properly presented to students. Insight into the difficulties of representing science accurately is vitally important for science education, and this is a topic that educators should deal with.

Chapter 13

Misunderstandings about science

Scientific Papers

Some sociologists believe that scientists misrepresent science in research papers and textbooks--that they do science one way, and describe it another. They have concluded that scientists unconsciously use rhetoric and other techniques in their papers to give the sense of objectivity where it does not exist, to give their own work more weight than it deserves, and to give the impression that theirs is a historical account of what happened when it is not. I will describe some of their observations and discuss explanations for them.

Various sociologists argue that, although scientists give the impression that they are simply reporting to their audience, they are actually trying to convince them. Rhetoric is the tool they use, either consciously or unconsciously, to persuade their readers (Latour, 1987, Woolgar, 1989, Cantor, 1989). Scientists use an impersonal tone to give the impression that: (a) nature is speaking directly to the reader; (b) the data are more stable than they really are and (c) the scientific methods used were determined more by nature than by the scientists themselves (Cantor, 1989; Prelli, 1989).

A number of techniques can be used in a paper to make it seem as though nature, rather than the scientist, is driving the process. It is usual to use a passive voice and to "report" results rather than "argue for" them, e.g. "the data show that .." rather than "We show with these data that" (Prelli, 1989). Similarly, scientists highlight their own explanations and play down, or leave out, alternative accounts (Prelli, 1989); they leave out descriptions of the actual research contexts; and they don't report false leads and unsuccessful procedures. Techniques of this kind, when added together, give the impression that the whole process is less subjective than it is.

Gilbert and Mulkay (1984) argue that words are selected carefully, if not consciously, to persuade. For example, an author calls an explanation he disagrees with, an "assumption," and leaves out supporting references, while he calls his own views "results," and adds supporting evidence. In casual conversation scientists are more tentative, but still use words that link their own theory with the truth and the evidence. In one study Gilbert and Mulkay (1984) found that two biochemists with opposing views on chemiosmosis (a mechanism involved in cell respiration) each talked as though he saw the evidence directly, but that his opponent was wrong because of personal failings. Each used statements like: "the facts are pretty clear experimentally" when speaking about his own side of the argument, but referred to the opponent as having a "strong personality," or being "misled by publications which have not been subject to proper refereeing" (Gilbert and Mulkay, 1984: 68).

Latour and Woolgar (1979) described what they called "the paradox of persuasion." The paradox is that although scientists write papers to persuade their readers, they will only succeed if nobody realizes that persuasion was used. Not only is a scientific report less objective than it seems, it is also less of a historical description than is claimed. Scientists seem to be writing a factual historical account of events, but they leave out much of the detail necessary for a truly historical account, and they only report their successful work not the false leads and mistakes.

These sociologists have made some interesting observations about scientific literature: first that scientists write in a stylized way to persuade others of their point of view rather than just reporting what they see; second that they emphasize the logic and objectivity of their work, and the evidence supporting it, more than seems to be justified by the real situation; finally that scientific papers are not the historical accounts that they appear to be. Some conclude that scientists are inadvertently fooling themselves and each other. These sociologists question the validity of scientific knowledge (Woolgar, 1989)

However, while the observations are interesting, the conclusions are not valid. We can find other, reasonable explanations for the same observations, by looking further beneath the surface than these sociologists have done. While they correctly observe that scientists *do not* write a proper historical account of their work, they ignore the fact that scientists *are not tr*[illegible] to write a real historical account in the first place. Scientists are actually trying to write a logical, lucid account, carefully supported with evidence. A historical account might be more honest, but it would also be wasteful and hard to follow. It is more effective to write a reduced and modified report that gives the essence of arguments, but leaves out the confusing clutter of everyday detail.

We can also question whether there is anything wrong with using rhetoric, and whether it is really designed to "persuade," or simply used to give "good reasons" for accepting the arguments of the author. Prelli argues that in science there is always some uncertainty, and scientists continually make choices about issues, like which problems to work on, how to formulate the questions they ask, which claims to emphasize. So it is reasonable to use rhetoric to bridge differences in understanding or opinion. In fact, he says, scientific discussion, if it were just rational or logical, with no rhetoric, would be narrow and abstract (Prelli, 1989).

Prelli also questions whether papers really do misrepresent science. They are written for other scientists, not the general public, and we can assume that other scientists understand how science is done. Therefore the rhetoric used in science must be acceptable to other scientists. Misrepresentations in papers are not serious if the information given is such that the experiment can be replicated. Scientists build their own work on the results of others, and would be impatient with any false claims that cost them time and money. So probably scientific papers do not misrepresent science in any way that interferes with the effectiveness of research. Scientists themselves have always understood what is happening when they write papers. For example Howard Florey said in 1965:

> "We all know that when we compose a paper setting out discoveries we write it in such a way that the planning and unfolding of the experiments appear to be a beautiful and logical sequence, but we all know that the facts are that we usually blunder from one lot of dubious observations to another and only at the end do we see how we should have set about our problems" (Florey, 1965, Quoted by Macfarlane, 1979: 304).

Scientists are following a style that they all understand and find useful. They are not misleading themselves and other scientists in this process, but they do sometimes mislead outsiders. The traditional image of a research paper as "a straightforward reporting of results" has led to a misunderstanding of what happens in science. A paper is not just a record of observations and conclusions; rather, it translates and condenses the work (Cantor, 1989). But whatever its value to scientists, the description of science, as presented in papers and textbooks, gives a picture that is misleading to students. The question is, where will we find a better image?

Experiment Is Forgotten

Scientists do not talk equally about all aspects of their work, and this has led to further misunderstanding about science. Scientists tend to give incomplete descriptions of their experimental work and practical experiences. Microbiologists become so accustomed to their microscopes that they look at and discuss the bacteria they see without ever mentioning the microscope. In fact, they give the impression that they do not even notice the microscope.

This phenomenon has been described by both historians and sociologists. Latour and Woolgar (1979) called it the "paradox of expertise" and described a biochemistry laboratory in which a great deal of work was done by technicians to collect data, but once the data were collected and converted into numbers on a graph, the lab work was quickly forgotten and not mentioned again. Only ideas, theories and reasons were discussed. The historian, David Gooding, also noticed that, once Faraday could explain his concepts and was accustomed to the methods that would get certain results, he stopped talking about the methods, and almost seemed to forget them. He seemed to remain aware only of his results (Gooding, 1989b).

If experience is so important to science, why do scientists ignore it? There are several valid reasons. The simplest is that experience is hard to describe because so much of it is tacit knowledge that is hard to put into words. For example, most of us would find it hard to explain exactly how to keep our balance on a bicycle. The second reason is based on the relationships between theories, phenomena and data in science. Theory is based on the existence of the phenomenon, not on local experimental data. Once experimental data have shown that the phenomenon exists, it is logical to forget the distracting experimental details (Nickles, 1990). As an example of this, the ability of penicillin to destroy bacteria, while not harming humans, is a now well established phenomenon, but local data did not always support it. When penicillin was first tried on patients, it often did not work, for a variety of reasons. The sensitivity of penicillin to stomach acid and heat, allergic reactions of patients, and resistance of some bacteria to penicillin all kept penicillin from working. These experiments provided the local experimental data that did not support the existence of the phenomenon. Now that scientists have seen enough evidence to convince themselves that the phenomenon really exists, they will mainly ignore local data.

This is an important issue for science education. When an experiment done by students does not work, and they do not see the expected result, they should not be allowed to think that they have disproved the theory. Nothing has happened except that their local results did not show the phenomenon. We should emphasize to them that their failure to get a result is a reflection on their local efforts, not on the theory or the phenomenon. Teachers should not lead inexperienced young students to expect to automatically get results that even experts may find it difficult to obtain (Hacking, 1983). All students are doing in their laboratory experiments is trying to see the phenomenon for themselves. They are not proving or disproving theories, and should not be led to think they are.

There is a third reason why scientists do not discuss their experiences completely, and it is based on how people learn. It is easier to see the relationship between concepts, by ignoring all other details. The scientist clarifies his theory for others by reworking his descriptions, so that the phenomenon stands out and the experimental methods, used to obtain it, disappear (Nickles, 1989a). Scientific knowledge must be separated from its local context, so that it can be readily understood by people who didn't see it produced. Nickles calls this process "cleaning up" the data for presentation. In other words, other people can't understand the important issues if they are distracted by a "clutter" of details that really apply only in the local context. This explains why scientists write scientific papers giving a logical explanation rather than a historical account of their activities.

In our schools, we want students to see the central issues and yet, at the same time, to have the experience of doing experiments. It is valid to teach "cleaned up" knowledge because this removes the "distracting clutter" of detailed experience, and it allows students to see the issues better. On the other hand, during the cleaning up, much of the uncertainty, excitement and intensity are lost.

The "Out thereness" of Scientific Knowledge

The unsettling fact remains that science is not as it seems, and that even scientists (who should know) don't describe it accurately. Outsiders are confused by the apparent shift in attitude toward a theory or fact over time within the scientific community. A number of sociologists have noticed that during the development of a theory, some magic point seems to be reached (closure) when scientists suddenly change their attitude toward the theory. Before that point, they are uncertain about it, critical of the methods used to study it, and not at all sure it is true. After that point, they accept the theory without question, and assume that it was "out there" all along waiting to be discovered. Some sociologists believe that the shift in attitude demonstrates that scientific knowledge can't be considered true, and that the appearance of truth is maintained by unintentional tricks through which scientists fool themselves and each other. These sociologists would encourage members of the general public to distrust scientific claims.

Scientists give the impression to outsiders that their attitudes toward scientific facts change as time goes on. There are reasonable explanations for this; it is not as odd as some sociologists would have us believe. The radical sociologists have misinterpreted the apparent shift in attitude, so I will give my own explanation for it.

Sociologists have investigated the changing attitude of scientists by examining the scientific literature. Latour and Woolgar (1979) followed individual claims made by scientists in scientific papers, from the time they were first mentioned, until they were accepted as true by the scientific community. The term "claim" is used by sociologists but scientists would call the same thing a "statement of fact." After a claim is made, it may be ignored by other scientists and disappear from the literature. However, if other scientists believe it is true, it is referred to in increasingly confident terms, until finally it is not even questioned or noticed, just considered as background knowledge. Latour and Woolgar (1979) found that the words used to refer to the claim change with time. Initially, a speculative tone is used (e.g. "Florey has suggested that penicillin may be effective against disease"). Then at a later time, statements about the claim point out "what is generally known" (e.g. "there is evidence to suggest that penicillin is effective against some diseases"). After this, phrases like "generally assumed" or "reported to" are used (e.g. "penicillin is generally assumed to be effective against Gram-positive bacteria"). In the next stage the claim becomes part of accepted knowledge and appears in text books. Tentative words are no longer used (e.g. "penicillin inhibits growth of Gram-positive bacteria"). The claim has become an uncontroversial fact.

The kind of evidence used to support the claim also changes as it is better accepted. Latour and Woolgar, (1979) say that, initially, a claim is strengthened if it is accompanied by a reference, saying when and where the evidence was gathered. But a point is reached when the claim is strengthened by removing the reference. At this point the claim is given a life of its own by removing it from "the time and place of its production" (Latour and Woolgar, 1979: 175). When it is finally accepted as a fact, this knowledge becomes part of the background, and is completely taken for granted.

These observers find it amazing that scientists change their attitude toward a claim so completely. They believe that when scientists see a claim as tentative at one time, but true later, they must be misleading themselves and others. This process of separating facts from their sources of discovery makes them hard to trace, and increases the sense of "out thereness" about them i.e., they were out there all along waiting to be discovered (Latour and Woolgar, 1979: 176). Since these sociologists are relativists, they argue that the sense of out thereness is the *consequence* of scientific work rather than its *cause* (i.e., the sense of out thereness has been developed by removing reference to where it was discovered). Scientists seem to have been relativists before, but realists after.

By identifying this changing attitude toward knowledge, Latour and Woolgar contribute to our understanding of science, but their conclusions are wrong. They have looked at *evidence* and mistaken it for *cause*. Scientists do change the words they use to describe a claim, but these "changed words" are simply evidence that they are beginning to believe the claim is true; not the reason they think it is true. Scientists believe the claim is true because its validity has been checked, and other evidence has accumulated to support it. So there are a variety of reasons for accepting a claim, and as confidence increases, scientists begin to use words that reflect that confidence.

Outsiders have difficulty understanding scientific theories, and they can be convinced by the arguments made by sociologists because the examples chosen are hard to follow. If Latour and Woolgar describe a hormone none of us are familiar with, then suggest that this hormone exists only in the minds of scientists, and explain that scientists have fooled themselves into believing it exists, members of the general public are not in a position to argue. However, if we take an example that is familiar, and apply their reasoning to it, the situation changes. Before 1940, penicillin did not seem like a possible cure for disease, and in Latour and Woolgar's terms, scientists were relativists about it. But after 1940 scientists assumed that the effectiveness of penicillin was "out there' all along waiting to be discovered, and everybody asked why Fleming and others didn't see its possibilities earlier (scientists had become realists about penicilin). From this kind of example Latour and Woolgar claim that scientists have convinced themselves that penicillin is a great medicine by changing the way they refer to it in the literature But such an explanation totally ignores the many kinds of new evidence that made the scientific community accept penicillin--like the thousands of people who were cured Words used in the scientific literature were not the reason scientists believed in penicillin, they were simply evidence that scientists believed in it. The reasons for the belief can be found elsewhere.

These kinds of views about science have a big impact on science education The books are easy to read, the arguments are intriguing, and the books are on the recommended reading lists, produced for teachers by the Nova Scotia Department of Education. Increasingly, members of the general public, including teachers, believe that scientific knowledge is subjective and tentative.

The issue is one of definition and degree. Scientific knowledge is tentative at a theoretical level, but not at the practical level where scientists use it As described earlier, science is so powerful because knowledge is checked and rechecked. By the time any important concept is taught in science classes, scientists are quite confident of its validity at a practical level; it is not tentative except at a very general level.

Chapter 14

Reconstruction

Yet another way in which science is confusing is called "reconstruction". This phenomenon, described by Thomas Nickles (1984, 1988, 1989a, 1989b, 1990), explains why there is so much misunderstanding about science, and why science is so hard to teach. It is the deceptively simple process in which fresh scientific knowledge is constantly reworked. Solutions to problems are reported with small changes in slightly different contexts, and they are seen slightly differently each time as the problem slowly becomes clearer and better defined. Reconstruction occurs in every discipline, but it has a greater effect on science and science education.

Nickles has described reconstruction as constant small change (Nickles, 1988). The typical image of science has been that it is a single-pass affair where a problem is deal with only once; where a scientist forms a hypothesis, tests it, draws conclusions, publishes, and never looks back. Instead, reconstruction (a multi-pass approach) is the norm; problems are reworked and are constantly changing. Old experiments seem to have new meaning in the light of new information. They may be repeated with small changes in the new context. New slightly different results may be obtained that lead to slight modifications in the theories. Barnes describes reconstruction as follows:

> "Science is not built like brick-builders build a house, with each brick checked for shape and soundness then permanently cemented into the building. Evaluation occurs again and again; every part of the structure of science is subject to

continuing reappraisal. Although of course some parts of the structure are scrutinized much less frequently than others" (Barnes, 1985: 42).

Reconstruction doesn't just occur when papers are written, it occurs constantly when experiments are planned, ideas are discussed and results are examined. Scientists do it without even being aware of it. It is a crucial part of science (as it is of learning generally) because our ideas are always muddled at first, and reconstruction is the method of clarifying them. However, it has made science hard to describe and teach. The process of applying and working on previous knowledge actually changes it, sometimes beyond recognition. It also removes the knowledge from its original context, so that even the scientist no longer knows where it came from or how it developed. Then it is reported as though reconstruction had never occurred, and the work had been done logically from scratch.

Scientists reconstruct the history of their scientific work before they publish it. They describe what they would have done, if they had known in the beginning what they know at the end (Nickles 1990). Scientists write as though they carried out a series of experiments in a single afternoon, when they really worked on the problem for months or years. They describe in their papers how they could have carried out their experiments if they had known the results ahead of time.

Reconstruction continues after the original result has been submitted for publication, or even after it is published, as errors made by individual scientists are caught by members of the scientific community. Reconstruction occurred a decade after penicillin had been discovered and abandoned by Fleming, in part because at that time no antibiotic harmless to humans had been found, and it was not clear that one ever would be. The discovery of sulphonamides changed the climate of opinion, and made scientists receptive to the potential of a drug like penicillin. This is described below.

> "The fact remains that his [Domagk's discovery of sulphonamides] was one of the most important medical discoveries that has ever been made, for it not only enabled us to treat and cure a whole series of very serious forms of infections, but of even greater importance, it showed us how wrong had been our ideas about how a successful chemotherapeutic agent was likely to act. As a consequence of this penicillin began to be thought of as a possible alternative. But let there be no doubt about it, without the sulphonamides to show the way, it is improbable that penicillin would have emerged from its obscurity" (Hare, 1970: 108)

Confusions created by reconstruction

Why does reconstruction, clearly such a necessary part of science, cause confusion? Partly because it may proceed in steps so small--too small to notice--and yet its effect is cumulative, so over time the discrepancy between the original and revised views becomes large. Partly because there is such a contrast between the apparent clearness and crispness of science and the actual fuzzy process of reconstruction. Partly because we tend to look back on science and think of all the processes as though they were instantaneous, when in fact they were complicated, changed relatively slowly and involved much effort and concentration. Nickles summed it up when he said "time has been sliced too thinly by those studying science" (Nickles, 1988: 36). There is also such a contrast between the assumption that facts, once accepted, are fixed in stone, and the reality that reconstruction may still be occurring. Mainly reconstruction causes confusion because almost nobody seems to notice it and take it into account

Reconstruction occurs in every discipline, during learning generally and in everyday life, so it sounds familiar and insignificant when described However, it has a greater effect on science and science education because science moves in only one direction and has such clear-cut right and wrong answers Once an answer has been found, the world is seen differently, and it is hard to recapture what the world was like before the change. Since most people are not really aware of reconstruction as it happens, it is hard to remember the exact history of events or describe them.

Reconstruction has special significance in science education because of the nature of science. There is a paradox--any description that does not take reconstruction into account automatically misrepresents what really happens in science, and yet reconstruction itself makes science almost impossible to describe accurately. Reconstruction is one of the most important issues for science education, but I have seen little mention of it.

Reconstruction and school science

Because of reconstruction, we do science one way and describe it in another Descriptions in textbooks or papers appear to misrepresent science because they give the logic of the ideas but not the actual process. This is a problem for students. How can we deal with it? We could teach the history of science and describe exactly how discoveries were made, including the false starts and the changes of ideas along the way; I described this earlier. But reconstruction makes it difficult to give a legitimate historical account. Scientists don't report their false starts and bad leads in the first place so how can we describe them in class? Moreover, it seems unreasonable to ask students to spend time on unsuccessful reasoning processes and faulty evidence, and we must keep in mind that the main reason why scientists present their results with the logic of hindsight is that we can then understand them more easily.

We should ask students to learn by solving problems themselves so they get some feel for science, but the feel will not be the same as scientists have. Scientists do solve small problems, but these are intimately related to other problems and to the constantly-changing theory. Whenever a student begins a problem in school science, he is coming in cold. In "real" science this stage would be the middle of the process because each problem currently encountered is a modification of a previous problem. Therefore, for the student, the experience is bound to be less immediate, interesting or logical than for the "real" scientist. It will also be harder for students to solve problems because a student with no background knowledge has no opportunity to use analogy, one of the main methods used by scientists. Use of analogy allows scientists to solve a current problem by borrowing from similar, solved problems. We can probably come closest to capturing the flavour of reconstruction, and give a sense of the interrelatedness of expert knowledge only by asking students to work on longer projects. Mainly, a knowledge of reconstruction should make us more sympathetic with the position of students. It should temper our expectations and modify what we ask of them.

Learning as Reconstruction

The term reconstruction has been used for science, but it is also appropriate for learning. When pupils learn they do not go over something once, learn it and never look back. Instead, they go over it again and again reworking concepts and gradually adjusting them. We should provide them with opportunities to reconstruct or develop their knowledge by allowing them to see concepts in different contexts. In learning, our ideas are muddled at first, and we clarify them by going back over them through a process of reconstruction. However, when we teach, we explain concepts logically not the way we learned them or the way students will learn them.

In learning as in science, much of the understanding occurs before it can be described or explained to others. As students learn, they know more than they are able to tell us (Woolnough, 1989). Students have difficulty in accessing newly acquired knowledge; it seems to be inert. In a paper about learning new scientific concepts Posner *et al.* (1982) have described a process that sounds like reconstruction. Students learn by abandoning the old concepts and accepting new ones but this does not occur all at once; it is gradual and piecemeal. After hearing a new theory students do not immediately gain a clear, well-developed grasp of it and its implications. They go through the slow process of taking a first step toward the new idea by accepting some parts of it, and then gradually modifying some of their other ideas, as they begin to understand the meaning better.

"Real change, particularly for the novice, is best thought of as a gradual adjustment in one's conception, each new adjustment laying the groundwork for further adjustments but where the end result is a substantial reorganization or change in one's central concepts" Posner *et al.*, 1982: 223).

We should give students an opportunity to rework their knowledge, by giving them a variety of assignments. They also need opportunities to work on them and explain them. It is unfair to assume that students have not learned new concepts, ideas or theories just because they are not immediately able to explain them to us.

The knowledge explosion and reconstruction

As described earlier, some science educators (Glass, 1970) argue that there is a knowledge explosion in science and theories become obsolete quickly, so it is more reasonable to teach processes than subject knowledge in biology. This argument, quoted below, appears in the 1990 biology curriculum guide for Nova Scotia.

> "The present de emphasis on content knowledge and emphasis on information-processing skills in our society is more imperative in science than in any other discipline. The "essentials" change rapidly as major scientific breakthroughs occur at an almost breathtaking pace. Research scientists in fields as diverse as lipid biochemistry, nuclear medicine or high-temperature superconductivity emphatically state that they cannot keep up with the knowledge explosion within their very specialized sub-disciplines. Science teachers realize they are preparing students for a world which sees scientific knowledge <u>double</u> every 2-3 years. Modern information technologies such as computer data-bases do, however, provide us with the tools to retrieve the most useful and up-to-date knowledge on

any topic. Our students need to be able to find, select, process, apply and evaluate knowledge" (Curriculum Guide, 118, 1990: 52).

The knowledge explosion seems to reduce the value of knowledge in biology, and gives teachers a reason for not teaching it. The mistaken impression is given that research in science is like replacing an old car with a totally unrelated new model. Scientific research does not throw out all old knowledge and start from scratch; it is a process of reworking existing and new knowledge, and gradually modifying old theories, until they eventually have a different look about them--this is the work of reconstruction. If we look at a theory after some time, it may seem different enough from the old to be called a new theory. But if we look closely at it, we find many of the ingredients from the old theory present in new combinations and new contexts--they may look different, but they are there all the same. The model for the evolution of scientific knowledge should not be a series of cars, but rather of genes. When you trace certain genes through a series of generations, you find that there is a mixing and reshuffling in each generation. Some alleles are passed on to the next generation and some are not. Of those that are passed on, some will be expressed and some will not. Recessive alleles may be hidden in some generations, but still be present. Some alleles, when they appear in entirely new combinations in different individual , will have different effects.

By comparing scientific knowledge with genes, I hope to illustrate that two factors working together--reconstruction and the integration of knowledge into networks form the basis for the development of new theories and insights This combination is a creative part of science because it allows synthesis. Scientific knowledge is an exciting part of active science; it is not just a set of inert products or conclusions. It is not correct to discount theories today on the grounds that they will be replaced tomorrow. They are worth teaching today because, even if they are replaced tomorrow, the new theories will be modifications of the existing ones. In fact though, by the time most theories are taught in schools, they are so firmly accepted that they are never replaced, and the fear that they will go out of date is groundless. In addition, since students, like scientists, learn by analogy, subject knowledge is a necessary background for further learning. It provides a context for the new knowledge.

There is no evidence that the knowledge explosion has anything but good effects for students. The reconstruction of knowledge that occurs in science carries over into science education. It is apparent from the analysis of textbooks, described earlier, that there is also reconstruction in the way we explain concepts to students, so our explanations become clearer as we understand the concepts better. Students are not learning more now, they are just understanding more.

Chapter 15

The Tentative Nature of Scientific Knowledge

We have moved in science education from one extreme to another in a relatively short time. We used to teach that most scientific knowledge was true, and we expected students to believe each theory we taught them. Now it is more common to say that all scientific knowledge is tentative, and we expect students to think critically by making their own decisions about which theories are true and which are not. These points of view are both too extreme, there must be a better balance. I will describe the different positions on this issue and look for a new explanation that could be used in science classrooms.

The old view, that we can test a theory against nature to find out whether it is true or false, is no longer accepted. Now opinions range widely, but the proponents fall into two main categories: relativists and realists. Realists believe that scientific theory aims to find out the truth about the world, and while it does not actually succeed all the time, successive theories make closer approximations of the truth. All scientists must belong to this group--they couldn't be scientists if they didn't. Relativists think that there are many truths, and different people can have different, but equally valuable, theories. Moderate sociologists (e.g. Barnes, 1982; Gilbert and Mulkay, 1984) are relativists who accept that the objects like electrons and penicillin are real, but question whether theories about them are necessarily true, and further, whether you can tell which theories are true and which are false. More radical sociologists (e.g. Woolgar 1989 and Latour 1987) question whether scientific theories are true, but also whether the objects studied are real in the first place. Woolgar (1989) also argues that scientists don't use rational methods but simply describe their methods to make them seem rational. He questions whether we can ever know what is true in science.

It probably does not matter where any one individual stands on the realist-relativist continuum. However, it appears that scientists stand on this continuum at a very different position than some science educators, and this difference is important to science education. In addition, scientists live in a different culture and attach a slightly different meaning to "truth" than do non-scientists. Scientists are realists on the small scale, day to day level, but non-scientists look at truth at a different level. Most modern teaching methods used in science education are based on a relativist stance.

A comment about the meaning of the word "theory"

A "theory" is an explanation of events but it presents a different impression in everyday speech than in science. In everyday speech, the term theory is often accompanied by "just" to designate that it is uncertain and unsubstantiated. In science, an explanation that is uncertain and untested is called a hypothesis, but once it is well supported by evidence and has been generally accepted by the scientific community, it is called a theory. Theories can be generalizations that are not really testable, although still well accepted, within the scientific community.

The relativist view

Relativists believe that scientific knowledge is provisional and uncertain. They point out that scientific knowledge has a short life span, and wonder how people can believe firmly in theories when they know that these theories will later be replaced by others. They also argue that scientific knowledge is social, meaning that scientists make assumptions (take knowledge for granted) and have biases. These assumptions and biases affect a scientist's observation and judgment even though he is not aware of it (Feyerabend, 1975). If all observation is theory-laden and scientific judgment is biased, then scientific knowledge is not dependable.

New realists--with a compromise view of knowledge

The views expressed by relativists have been effective in shifting the definition of scientific knowledge. Realists no longer see scientific explanation as linked to ultimate truth, but instead as an explanation that everybody agrees with, at least temporarily. Similarly, they no longer think that scientists compare a theory directly with nature to decide on its truth, but instead that they compare theories to each other and chose the best one available (Brown, 1989). A new definition has developed of science, as a rational activity that aims for the truth but does not always achieve it.

Are scientists objective?

It would be naive to believe the picture created in the past that scientists are objective, unbiased and interested only in the truth. A number of studies carried out by psychologists found that scientists are no more objective than non scientists. Scientists don't look for falsifying data or abandon favoured theories in the presence of falsifying results (Gilhooly, 1988). However the scientific community as a whole has mechanisms (described earlier) to correct errors made by individual scientists, and the public nature of science protects it to a large extent from biased research.

Uncertainty--a temporary phenomenon

A number of factors make it hard for scientists not only to find the truth, but also to know whether they have succeeded in finding it. Ideally, scientists would choose the best theory after all possible alternatives and evidence are available; but this rarely happens. In practice scientists make decisions in real time, choosing from whatever theories happen to be available at that time, using evidence that is imperfect. The actual choice is always limited to a very few theories, so decisions are easier than they seem, but perhaps less perfect than imagined. As scientists work, they don't know where they are going, and the result is uncertainty. As Gooding has described it,

> "Doing science is like following a trail blindfolded. Scientists stumble along picking up occasional clues, and drawing conclusions so they can decide where to go next" (Gooding, 1989a: 126).

We all live with uncertainty about the future, but science differs from most other disciplines because scientists assume there is only one answer to every question, and that answer depends on *nature* rather than on the scientist. Therefore, it is not surprising that, at the beginning of an investigation, scientists are tentative about the truth of their theories and accept correction readily. Mistakes will surely be made and later corrected. Current theories sometimes have to be abandoned because they are not supported by the evidence. Others may, by their very nature, continue to be tentative.

There is no embarrassment in having a favorite theory corrected, and scientists see science as a process of learning about the world, not of forming theories and having them corrected (as observers assume). It is natural that scientific knowledge is constantly changing, and that theories must be added to and revised, and even rejected. Scient see it as knowing a certain amount about the world one day, and learning more the next. This process of learning in science is not at all analogous to the process that takes place in science classes. In real science, there is nobody comparable to the teacher (the person who knows all the answers). Scientists are on an equal footing they are all uncertain Initial evidence and proposals are tentative, and when new evidence contradicts a theory, everybody, including the person who first proposed it, sees the eve ' as simply learning something new. However, as evidence mounts, uncertainty disappears, and finally scientists become quite confident that certain theories are correct. What initially appears to be a relativist approach to knowledge, becomes a realist approach.

The meanings of truth

Observers of science (philosophers, sociologists and historians) think there is no guarantee that science finds the truth. Yet if the goal of scientists is to find the truth, and it is not a realizable objective, why are more scientists not discouraged? Why do they remain so optimistic? I will try to explain this apparent gap between scientists and observers of science by describing different meanings of truth and time. Scientists work within a unique culture so it is not surprising that they have their own distinct understanding of the truth. There are different kinds of truth. First I will describe the difference between small scale everyday truth and truth on a large scale; then I will analyse how scientists distinguish between present truth and eternal truth.

Small scale truth and universal truth.

In the introduction to a book about reality, Lawson (1989) pointed out that scientists work with everyday truth, but observers of science usually think in terms of eternal truth. This distinction is very important, and needs to be developed further. Most scientists, if challenged, would probably agree that on the general, universal level they can't guarantee that scientific theories are true. However scientists don't examine science from the top down, as observers do, they work from the bottom up. They work with small facts on a daily basis, and they build the facts in such a way that larger theories emerge. Truth, as scientists view it, refers to individual observations and conclusions (whether a strain of mold produces an antibiotic, what effect it has on certain bacteria, what kind of damage it does to the human kidney, etc.). Without a belief in truth at this level, scientists could not carry on their occupation. If we agree on truth at this day to-day level, then we know it is possible to understand the world, and this gives us a basis for our larger theories. Observers of science tend to ignore science at this level, and look only at universal theories.

So why can't we just accept (as the positivists did) that facts are true but larger theories can't be verified? This distinction is impossible because of the relationship of larger theories to facts. Hesse compared scientific knowledge to a web, but for this discussion I will compare it to an onion. On the inside layer (at the core) are facts we know are true. When these facts (leaves) are arranged together (wrapped around each other as the leaves of an onion) certain more general facts are supported so we find a second layer of fact or theory (outside the first and supported by the first). It is more general, more theoretical, but still soundly based because of its relationship to the layer of solid fact beneath. The distinct arrangement leads to further, more general theory (on the next layer out) which is also supported by the theories and facts beneath. Outsiders usually look at these general theories only from the outside and, on that basis, challenge the truth of the theory. And at this level, scientists may have difficulty defending it. But if the levels (leaves) are peeled off and examined, it would be hard to say at which le· truth can be counted on, and where it gives way to unverifiable theory. Scientists believe that basic underlying facts are true and they can find no arbitrary cut off point between truth and general theory. Truth has different meanings because observers of science look at theories only from the outside while scientists look at them from the inside and the two groups see different kinds of truth from these different perspectives.

The truth will out

The other gap between scientists and non scientists relates to the time scale intended. Truth has an eternal ring to it, but not in science. Scientists appear to be definite about their theories, but they are much more flexible than they seem. Truth is defined in a more provisional way in science than it seems to outsiders. Scientists always temper their acceptance of a theory with "given our present knowledge". I will explain this by describing how scientists view time.

Scientists are realists about the day-to-day truth of scientific knowledge, but do they believe in the eternal truth of their theories? The answer is yes, but an unexpected kind of yes. In our general culture, when a person believes a theory is true, she normally believes that it will remain true forever. Scientists have a different slant on this. It is not that they think current theories are true and will remain true forever; instead they think that in the long run we will know whether a theory is true--the final decision about truth will come in the future. And when we do know the truth, it may or may not be what we think is true today. Gilbert and Mulkay (1984) called this "the truth will out device," and suggested that it allows scientists to cope with uncertainty. However, I think they underestimate its importance. It is not just a coping mechanism, but a good description of what scientists believe happens in science, and they are probably right.

Time is underestimated in science and every stage seems instantaneous. Some scientists have contributed to this impression by describing discoveries as though they resulted from a flash of insight. But knowledge evolves slowly, so this image of sudden, spontaneous discovery is wrong. Not only is discovery not instantaneous, but neither is closure (the point at which the truth of a theory is no longer questioned in the scientific community). Some observers assume that closure marks a boundary where a fact is never questioned again (Latour, 1987 Woolgar, 1989), but it is really just the point at which a fact is accepted and used. The same fact can be reconsidered and rejected any time later. In fact, if scientists thought decisions were final, they would probably be less willing to make them in the first place, and closure would probably disappear. The flexibility in the process leads to confidence in the knowledge produced. So closure is not what it seems to outsiders, it exists only because it is not final.

Observers of science think the story of science ends with closure, but scientists think it doesn't end until "the long run," and that, although scientists must work and make decisions in the short term, truth operates in the long term. They can comfortably accept theories as true for now, because they are confident that any errors will eventually be corrected. It doesn't matter whether science is purely rational or social in the short run, because in the long run the answer will be rational, as local social factors cancel each other out. With this kind of reasoning, truth is not an issue in the short term because it can't be known for sure; and it is not an issue in the long run because all theories will be true in the long run, as the social factors that interfere with truth in the short run are neutralized and drop away. This may explain why scientists ignore these discussions about truth. They operate on a day-to-day basis where the question of ultimate truth is irrelevant because it cannot be solved. Truth will eventually be known, but "the long run" (or tomorrow) never actually comes, so it can't be dealt with in any practical way.

Because non scientists don't realize that science is a slow process in which knowledge evolves, they take the truth too seriously. They ask for an instant definition of truth when it can't be given, and think that theories are either permanent or tentative, when they are really neither. To a certain extent, truth in science is under attack, not because of the qualities of science, but because it is on the edge of a discussion about language and knowledge. This is a discussion that has little to do with science itself, but it is shaping the image of science in society generally. While teachers must respect the views of society generally, not just those of scientists, it would be a shame to misrepresent science by presenting students with views that are based on a misunderstanding.

There are two meanings of tentative: initial theories are tentative before sufficient evidence has been collected, and all science is tentative on a general level. In addition there is a distinction between a theoretical and practical meaning of tentative. On an abstract level, all theories are tentative because they can be changed later if evidence warrants, but on a practical level science would fall apart if scientists did not accept well-supported theories as true.

It is fine to teach students that all scientific knowledge is tentative on a general level, but only if you also encourage them to accept the theories they learn in classrooms as true. The definition of scientific knowledge, as *either* true or tentative, is damaging.

CONCLUSIONS

Throughout the thesis, I have argued that a unique image of science has developed within the education community. Modern teaching methods have been developed that are compatible with this image but not, I believe, compatible with science. I will summarize these issues.

Definitions of science

Within education science is defined as a process and a way of thinking, rather than a body of knowledge. Scientific knowledge is the product or conclusions of science rather than an active part of it. The knowledge explosion in science ensures that knowledge goes out of date quickly so current knowledge is not valuable and teachers are justified in reducing the amount they pass on to students. Associated with the idea that scientific knowledge goes out of date and is replaced, is the view that it is not necessary to teach it. If we teach students the processes of science and the tools to retrieve knowledge, they will be able to find and use whatever they need in the future. The idea that scientific knowledge is tentative, thus somehow less valuable, has encouraged the view that each student should make her own decisions about what to believe.

I have tried to demonstrate that scientific knowledge is not just the product or conclusions of science. It plays an active part in all aspects of science, so it would be more accurate to define science as a body of knowledge about the natural world that is developed using logic and evidence. Science is so successful, not because of its methods, but because it accumulates knowledge into a knowledge network and allows scientists to reorganize it and build on it. Knowledge is not the product of science but the most active part of it.

There is no evidence in biology, and apparently not in science generally, that real scientific revolutions occur, where old knowledge is overthrown by new. Instead, new information is integrated into existing knowledge networks, and new understanding is produced. Students must have a basic knowledge of the theory in a discipline. They cannot learn the methods of science now, and acquire specific knowledge later. Scientific knowledge is tightly integrated, and each theory or fact depends on many others. It is simply not possible to pick up and understand facts or theories in isolation. Without a proper foundation in disciplinary knowledge, there will be little understanding.

The general assumption that all scientific knowledge is tentative may be correct at one level, but it does not reflect the complexity of this issue, and is not a useful concept for either science or education. In practical terms, theories are more or less tentative depending on the circumstances. Scientists are very uncertain about their theories when they first propose them, but as evidence accumulates they become more confident in them. Once a theory has been tested, rechecked, used in other contexts and accepted by the scientific community, it is considered to be true *at a practical level.* Scientists would not consider the theory to be tentative, even though they would admit that it could be changed if future evidence contradicted it. All major theories and facts that we present in science classes have been well supported by evidence and well accepted within the scientific community. Scientists believe these theories are true, so we should also teach our children to accept them as true at a practical level

Sources of misunderstanding in science education

These two definitions of science developed, partly because it is hard to understand how science operates and partly because there is some conflict in values between the culture of science and the distinctive culture in education. The communal and authoritarian structure of science makes it successful but these are the features that educators dislike. Educators value independence and the right of every individual to question every decision. They want students to judge every theory for themselves, they think that is where the motivation lies. But scientists want students to understand the theories; they think the interest comes from learning something new. Whose culture should we present to students when we are trying to teach science? We must teach both, we should let students experience the culture of science, but since they are students rather than scientists, the culture of education is also important.

Educators gradually redefined science by unintentionally introducing concepts from education into their definitions of science. This redefinition has taken place too slowly to notice, but it has led educators and scientists to have totally different images of science and different philosophies for teaching it. Within education, the introduction of the project method in 1918, led to a reversal of priorities making the experiences or method of learning more valuable than subject knowledge. By 1960, this emphasis on method rather than knowledge was transferred from learning generally to the definition of science. Scientific knowledge was removed from active science by calling it the "conclusion" or "product" of science

Science education is influenced by forces other than science itself (Roberts, 1988) It will always depend on compromise, but the participants making the decisions should understand exactly what kind of compromise they are making. The danger today is that the participants are not speaking the same language, but think they are A gap has slowly developed between science educators and scientists but neither group seems to realize it is there.

Finding the Middle Ground

We need a middle-of-the-road approach to science teaching, with a balance between the teaching approaches. Dewey said.

> "Mankind likes to think in terms of opposite extremes It is given to formulating its beliefs in terms of *either-ors*, between which it recognizes no intermediate possibilities" (Dewey, 1939: 5)

Furthermore, when individuals accept a theory or stance, they are often polarized by it so they automatically object to all features of what they see as the opposite view (Dewey, 1939; Dearden, 1968). Dewey suggested that those who support one form of education tended to automatically discount any ideas, even good ones, related to the other form. In effect they were polarized into an inflexible view by their antagonism

> "In spite of itself any movement that thinks and acts in terms of an 'ism becomes so involved in reaction against other 'isms that it is unwittingly controlled by

them For it then forms its principles by reaction against them instead of by a comprehensive, constructive survey of actual needs, problems, and possibilities" (Dewey, 1939: 6).

Dewey was, at the same time, opposed to a compromise that would sacrifice some of the best features from each stance. David Braybrooke (1982) suggested that a different kind of compromise can be formed if we "transform the issue by supplying further proposals" (Braybrooke, 1982: 147) Such a compromise would combine some of the best features of each position. There is a middle route that uses the best of the traditional as well as the best of the new approaches to science teaching, and makes the most of an understanding of science while at the same time recognizing the needs of students.

Effectively, we have a course-grained view of the world with just a few paradigms. We look for large scale solutions in education because it is hard to examine individual ideas away from a paradigm. However, progress in science teaching needs a fine grained view of the world because science education depends on both science and students Each step depends on small changes that take into account what is logical given the nature of science and what is possible given the nature of children.

Difficulties in teaching science

These are difficult times in science education. Science is hard to teach because it is a demanding topic. In addition our society now provides greater personal freedom with both positive and negative effects on students. We must acknowledge these difficulties before we can cope with them, but it may also be possible to use one to help overcome the difficulties of the other.

Changes in society

Recent changes in society have had enormous impacts on education. Children watch television more and read less, while schools are based on a written culture. Individuals have greater personal freedom and this is beneficial but it also means that children are influenced less by the school and they grow up with less discipline, structure and security in their lives. As teachers try to deal with these changes, they may be attracted by the newer teaching methods, which decrease the quantity of structure we impose on students, reduce the amount of effort we ask of them and give students more freedom. However, these methods are probably a **result** of the changing times (and a symptom of them) not necessarily a **solution**. Instead we should fill the gaps to make up for some of the things children have lost. Reducing the structure and framework of the curriculum may not be the answer.

Structure of science

Science is hard to learn because it consists of a tightly knit framework of knowledge, a distinct language, and an abstract subject matter. Barnes (1985) suggests that science education is like an apprenticeship in music. At the beginning students work very hard to develop the skills they will use later. The theories and problems in science are similar to finger exercises that music students practice to develop their skill. In both cases the drudgery comes at the beginning and the rewards come later. Barnes calls it "the sacrifice and the promise of scientific training" (Barnes, 1985: 23).

Perhaps moving toward the culture of science is a solution to the current malaise in education, because it can supply some of the discipline and structure that is lacking within our general culture. This will only be successful if we can also rediscover a sense that scientific knowledge is important and central to science and look for ways to make it interesting for students. We should identify what fascinates scientists about science and make the most of these features. The excitement of science lies in constant change, challenge, uncertainty and fast pace. Students may have to forgo the enjoyment of making important decisions and judging theories in their science classes, but it is replaced with the fun of constantly learning new things about the world. Students within a branch of science may learn the same knowledge, a common language and the same skills so they can communicate with each other. They can learn how to work together for a common goal, accept the judgements and authority of others for the sake of more dependable knowledge, and learn how to accept correction from others and build on it.

A concentration on the knowledge of science may contribute to the sense of structure for students, but this must also be accompanied by experiences in science. We should encourage inquiry among our students, not to learn major concepts but to study smaller problems that use these concepts. Just because students cannot discover theory through activities, does not mean that they cannot inquire about a topic that interests them. They can work on open-ended problems where it does not matter which answer they get. Similarly we can encourage students to make judgment about issues and situations in science as long as these are small issues that they understand well

Recapturing frontier science

The real challenge of science teaching lies in recreating the exciting discovery stages of science, without claiming that well-accepted theories are tentative, pretending that inexperienced students are scientists, or giving the impression that this is all of science. Inquiry learning tries to reverse the closure process and take students back to the local experience, but this leads to confusion. Constructivist approaches try to allow students to see all the data and judge the theories for themselves, but students can't judge the data properly when they are parachuted into the middle of a process they don't understand; moreover, once theories are known and generally accepted, it is unrealistic to pretend that students can assess them all over again, without bias. These approaches are too ambitious, but they are on the right track. They are likely to be more successful if they are used to inquire and make judgments about smaller issues in science. Developing these kinds of experiences is one of the most interesting challenges in science education.

Appendix 1

Summary of the Curriculum of Nova Scotia

The curriculum for high school biology is summarized below. It was published each year from 1893 until the early 1950s in The Journal of Education, and after that, in books produced by the Department of Education. As much as possible, I have retained the words used in these publications.

1893-1910

Botany was taught in grade 9, Agriculture in grade 10, Physiology in grade 11 and a choice of sciences including Botany and Zoology in grade 12. The curriculum and most of the textbooks remained the same from 1893 to 1909.

Grade 9 Physics and Botany

1893-1899 Gray's *How Plants Grow*, substituting for the details of *"Flora" part II*, common or prescribed native plants. Drawing of parts of plants.

1899-1910 Botany as in Spotton's *High School Botany* or in Gray's *How Plants Grow*.

Grade 10 Chemistry, Mineralogy, or Agricultural Chemistry

1393-1899 *Agricultural Chemistry* as in Tanner.

1899-1910 *Agriculture* by James

Grade 11 Physiology and Physics

Physiology text Martin's *Human Body and the Effects of Narcotics*.

Grade 12 Scientific side. Physics, Chemistry, Botany, Zoology, Geology, Astronomy, Navigation, Trigonometry, Algebra, Geometry.

1893-1910 *The Essentials of Botany* by Bessey, with a practical knowledge of representative species of Nova Scotian flora.

1893-1899 Dawson's *Hand-Book*, with dissection of Nova Scotian species as in Colton's *Practical Zoology*.

1899-1910 Zoology as in Ontario High School Zoology, *Zoology* (Ramsey Wright) or Dawson's *Handbook* With dissection of typical N S species as in Colter's *Practical Zoology*.

1910-1918 The curriculum was revised in 1910

Botany was taught in grade 9 and grade 12 No Zoology was taught.

Grade 9 Physics and Botany

Spotton (except chap XIX) (used 1899-1918) and the study of wild plants of the phenological observations, with Pteris, Aspidium, Asplenium, Onoclea, Osmunda

Grade 10 Chemistry

Grade 11 Physics

Grade 12 Sciences are: Physics, Chemistry and Botany

Bergen and Davis' *Principles of Botany* (used 1910-39)

1918-1934 The Curriculum was revised in 1918

Grade 9 Any two of: Botany, Agriculture or Physics

Botany Bailey's *Beginner's Botany* (MacMillan) and the study of wild plants of the phenological observations, with the more common ferns in detail (Spotton's Botany contains the most concise flora yet published for use of students).

Agriculture -Brittain's *Elementary Agriculture and Nature Study* M.P. Edition (Educ. Books Co). Second year course.

In 1932, grade 9 was included in junior high school and a general science course was taught. Omitted from further analysis since it was no longer in high school.

Grade 10 Physics

Grade 11 Chemistry

Grade 12 Physics, Chemistry, and Botany

Botany Bergen and Davis *Principles of Botany* (MacMillan)

1934-1939

Grade 10 Biology *Essentials of Biology* by Meier, Meier & Chaisson (Canadian edition revised).

Grade 11 Physics and Chemistry

Grade 12 Physics, Chemistry and Botany

Bergen and Davis *Principles of Botany*

1939-1941

Grade 10 Content and procedure as in the outline for this subject in the *Handbook to The Course of Study*. Text Meier and Chaisson's *Essentials of Biology*

Grade 11 Science - Physics and Chemistry

Grade 12 Physics, Chemistry, Biology, Geology and Botany are offered.

Biology, Mavor's *General Biology* complete. The examination in Biology will contain a great many options, so that teachers need not require pupils to study in detail all the orders discussed in the book.

Botany - Bergen and Davis's Botany (This course is likely to be discontinued after this year)

1942-1944

Grade 10 Biology Text: Meier and Chaisson, *Essentials of Biology*

Grade 11 Physics and Chemistry

Grade 12 Physics, Chemistry, Biology, and Geology are offered

Biology Mavor's *General biology*, Macmillan Company ($4.00) or Woodruff *Fundamentals of Biology*, Macmillan ($3.75). The examination in biology will contain a great many options, so that teachers need not require pupils to study in detail all the orders discussed in the book. Teachers may use other textbooks in biology of similar quality, provided the consent of the education office has first been secured. These books must be secured by teachers and pupils direct from the publishers

1945-1955

Grade 10 Biology Meier, and Chaisson's *Essentials of Biology*

Grade 11 Physics, Chemistry or Household science

Grade 12 Biology, Physics and Chemistry

Biology Woodruff: *Foundations of Biology*

1956-1965

Grade 10 Science

Science in Action Book 2 Unit 1; unit 2 (except chapter 8) unit 3 (except chapters 9, 10 and 11); Unit 4 (pages 300 to 324 only); Unit 5 are considered full year's work. Interested pupils should be encouraged to read the omitted units for themselves

Grade 11 Physics, Chemistry or Household science

Grade 12 Physics, Chemistry, Biology or Geology

Foundations of Biology - Woodruff

1966-1976

Grade 10 1966 Teaching guide biology grade 10 (University preparatory program)

In 1966 the BSCS (green version) was being tried out in some schools whose teacher had attended a special summer school. The other course was the traditional type of biology course using the text *Living things* by Fitzpatrick, Bain and Teter.

The first course in biology (ecology) - Change in living things through time, diversity of type and diversity of pattern in living things, the genetic continuity of life, the complementarity of organism and environment, the biological roots of behavior, the complementarity of structure and function, preservation of life in the face of change, science as inquiry, the history of biological conceptions.

The second course in biology (traditional) The nature of life, the basis of life, the relationships of living things, the taxonomy of plants, the flowerless plants, the higher plants, the taxonomy of animals, the invertebrates, the vertebrates, the human body, disease, heredity, conservation of natural resources

This has traditional subjects but also sections on fighting diseases, alcohol, narcotics, and tobacco, communities, conservation of soil and water, conservation of forests, heredity, includes Mendel's experiments, review of mitosis, meiosis, predicting heredity boy or girl? sex-linked recessives, identical twins, variation within species, environment.

1977-1987

Grade 10 **Biology 221** (General) For students who do not require a science credit for university entrance

Biology 421 (Academic) Two approaches are possible - an ecological approach and a traditional approach. While the ecological approach is recommended when feasible, the traditional is provided for schools where staffing or lack of suitable environments make is impossible. For students who do not wish to study biology further, process is as important as content. Topics include ecology, structural diversity in plants and animals and the cell. Optional topics are marine plants and animal , pollution, forest and wild life management, biogeography.

Biology 521 (Advanced) The BSCS green version biology program is the basis for this honours course. It is inquiry oriented and emphasizes an ecological approach. It is intended to be taught to highly motivated selected students who are able to study more theoretical material successfully and engage in more individual and group projects and prepare research papers and benefit from additional laboratory investigations. Topics include ecology, diversity of plants and animals, the cell, study of selected environments.

Grade 12

Biology 441 (Prerequisites 421 or 521 & Chem 431)

This is a continuation of Biology 421. Students may take it in the second year of high school. However, it is recommended that students who plan to enrol in this course be encouraged to take chem 431. Topics include: reproduction, cell chemistry and physiology, general vertebrates and vascular plants, human anatomy and physiology, and optional topics chosen among microbiology, embryology, current issues in biology, behavior or human behavior

Biology 541 Honours course

It contains a minimum of one BSCS laboratory block which emphasizes laboratory skills and scientific procedures a minimum of 5 of the 8 units listed are required This flexibility will enable course planners to take advantage of local resources Listed units include cell physiology genetics, animal growth and development plant growth and development, and human physiology, evolution, field ecology, animal behavior.

1988-1990

Grade 12 **Biology 441** The description is the same as from 1980-88 But human anatomy is included in this course because of its importance to all students It is expected to assist students in learning the biological knowledge on which a healthy life can be lived as well as providing a topic which is interesting and motivatin

Biology 541 Study is the same as 441 with the addition of other topics of interest to the students and their teacher

1991-1993

Grade 12 Biology 441 This course is designed to assist students in (1) understanding themselves as an organism in an complex and evolving biosphere (2) respecting the rules of biology through the way we treat our bodies and environment that we rely upon for survival. Each student should acquire a respect for the stewardship of life at both the individual and community level.

The fundamental ideas, processes and concepts of modern biological sciences are explored in Biology 441 through a curriculum which is organized through a Science, Technology, Society orientation. Core topics are energy relationships and transformations, regulation and control, genetics, technology and the future, and evolution and the patterns of change. Optional topics include independent study, behavior, toxicology, a locally designed unit, pharmacology and careers in science.

Biology 541 Core and optional topics will be the same as 441 except that all students must have multiple opportunities for independent study. In addition it is mandatory for students to complete a significant independent research project which relies for the most part upon experimental investigations.

1993-95

Grade 12 **Biology 441** The course is designed to assist students to develop an understanding of the fundamental science concepts and principles and to develop an awareness of the tremendous impact of biology and associated technology in society. Also, students should be aware of the roles and limitations of biological sciences, science in general and technology in problem solving in a social context. The fundamental ideas, processes and concepts of modern biological sciences are explored through a curriculum which is organized through an STS orientation. Core topics are energy relationships and transformations, regulation and control, genetics, technology and the future, and evolution and patterns of change. Optional topics include behavior, toxicology, a locally-designed unit, pharmacology and careers in science and an optional independent study research project.

Appendix 2

Summary of the Textbooks used in Biology in Nova Scotia

Grade 9

1893-1899 Gray's *How Plants Grow*, substituting for the details of "*Flora*" *part II*, common or prescribed native plants. Drawing of parts of plants.

1899 1918 Botany as in Spotton's *High School Botany*.

1918 1934 Botany - Bailey's *Beginner's Botany* (MacMillan) and the study of wild plants of the phenological observations, with the more common ferns in detail (Spotton's Botany contains the most concise flora yet published for use of students).

1918-1934 Agriculture - Brittain's *Elementary Agriculture and Nature Study* M P Edition (Educ. Books Co). - Second year course

1932 1934 General science -Snyder *General Science* Chapter XI to end.

Grade 9 became part of junior high school.

Grade 10

1893-1899 *Agricultural Chemistry* as in Tanner.

1899-1909 *Agriculture* - James

1910-1933 No biology

1934-1955 *Essentials of Biology* by Meier & Chaisson

1956-1965 *Science in Action* Book 2 Unit 1; unit 2 (except chapter 8) unit 3 (except chapters 9, 10 and 11); Unit 4 (pages 300 to 324 only), Unit 5 are considered full year's work. Interested pupils should be encouraged to read the omitted units for themselves

1966-76 There were 2 courses in Biology: *BSCS Green Version* and *Living Things*, Fitzpatrick

1977-1993 **Biology 421** Academic course. *Modern Biology* by Otto and Towle (1973), *Understanding Living Things* by Reimer and Wilson (1977), and *Biological Science* by Andrews.

Biology 521, Honours course. *BSCS Green version* (*Biological Science: An Ecological Approach* Fourth Edition (1978).

1993-1995 *LoRST, Logical Reasoning in Science and Technology*, Aikenhead, G. (1991)

Grade 11

1893-1910 Physiology text *Martin's Human Body and the Effects of Narcotics*

1910-present - no biology

Grade 12

Zoology

1893-1899 Dawson's *Hand-Book*, with dissection of Nova Scotian species as in *Colton's Practical Zoology*

1899-1910 Zoology as in Ontario High School Zoolgoy *Zoology* (Ramsey Wright) or dawson's *Handbook* With dissection of typical N.S. species as in Colter's *Practical Zoology*.

Botany

1893-1910 *The Essentials of Botany* by Bessey, with a practical knowledge of representative species of Nova Scotian flora.

1910-1939 Bergen and Davis' *Principles of Botany* (used 1910-39)

Biology

1939-1944 Mavor's *General Biology* complete.

1942-1944 Biology Mavor's *General biology*, or Woodruff *Fundamentals of Biology*

1942-1965 Woodruff: *Foundations of Biology*

1976-1990 The grade 12 program is divided into academic and advanced.

Biology 441, Academic. *Modern Biology* by Otto, and Towle (1973).

Biology 541, Advanced. *Foundations of Biology*, McElroy and Swanson, Editors (1968).

1991-1995 *Biology, the Study of Life, Third edition*, Schraer, W.D. and Stolz, H.J.

Appendix 3

Analysis of High School and College Textbooks for Subject Content

For each textbook, the percentage of the book (in page numbers) discussing each of the subjects shown below was calculated. It was fairly easy to decide topics belonged in each category, especially for subjects like genetics, evolution and ecology, but the assignment of topics was arbitrary in some cases. The categories are:

A. Total number of pages in the book.

B. Cell structure and function contains cell organelles, cell physiology structure of membranes and cell walls. It includes mitosis and meiosis, even though these subjects are often located near genetics in modern textbooks.

C. Chemistry and Biochemistry includes chapters that explain background chemistry and chemistry of organic molecules. It also includes discussions of cell respiration and photosynthesis, when the emphasis is placed on the biochemical reactions associated with these processes. Typical chapters might be: chemistry of the living cell, biological molecules, the flow of energy, cell metabolism, photosynthesis.

D. Organism structure and function includes the functions of organisms at the level of organ systems for both plants and animals. Typical chapters might be: life of the plant, movement of materials through the plant, growth and integration, the leaf and its function, roots and stems, water relations in plants, plant growth and responses, plant reproduction and development, how animals live, homeostatic processes, nutrition, movement, coordination, transport systems, excretion, respiration, nervous and sense systems, reproduction and development. There is some discussion about the application of this information for medical or other purposes in some chapters, but they remain in this category as long as the descriptions are not extensive. Animal and plant development remain in this category although they are sometimes grouped with genetics and molecular biology in modern textbooks. However, discussions about the expression of genes are included in the category of molecular biology.

E. **Diversity of organisms** includes descriptions of organisms (as whole organisms) or comparisons of organisms with each other. Typical chapters might be: sponges and coelenterates, worms, fishes, amphibians, reptiles etc., multicellular plants: mosses and ferns, the seed plants, the viruses, bacteria, protozoa, fungi, algae. Even when chapters discuss evolutionary history, they are included here if they are basically about organisms. For example, the following chapters are included in this category: prokaryotes and the origins of metabolic diversity, protists and the origin of eukaryotes, plants and the colonization of land, invertebrates and the origin of animal diversity and the vertebrate genealogy.

F. **Genetics** includes Mendelian genetics, the chromosomal basis of inheritance and human genetics.

G. **Molecular biology** includes the structure and function of nucleic acids, protein synthesis, genetics of microbes and DNA technology.

H. **Evolution** includes the theory of evolution, evidence for evolution, population genetics origin of species, tracing phylogeny and the fossil record. Chapters on origin of life are included here or in the chapter on chemistry and biochemistry dependirg on the amount of chemistry in the discussion.

I. Ecology includes discussions about the environment, biotic communities, interactions between organisms, populations, cycling of energy between trophic levels, ecosystems. Two kinds of discussion associated with ecology are included in the category of applications to society: discussions in early texts about conservation that do not include theory of ecology, and discussions in modern texts about the applications of ecology to social issues.

J. Applications of biology in society includes any discussion of the applications of biological knowledge to society. Typical chapters might be: tobacco and drugs, eugenics, medical microbiology, conservation of forests, farmland etc. and plant and animal sources of food. DNA technology is included in the molecular biology category, and human biology is added to the category on structure and function (unless clearly medical).

K. Behavior includes sections on instinct, learning, memory and social behavior. Nervous systems are found in the section on structure and function.

L. Scientific methods includes: The nature and logic of science, testing hypotheses etc.

Summaries were made of all textbooks written over specific time spans and standard deviation was calculated for the summary It is included in brackets after each percentage, to give an indication of variance within each time span. Variance is rather high in some cases (especially in high school textbooks) because all books written over a specific time period were included, even when they were written for different purposes.

Table 5. Subject Content of Textbooks, (a) College Books. For each textbook, identified by its first author and year below, the total number of pages (A) and the percentage of the book devoted to each topic (B-L) is listed.

A. Total pages
B. Cell
C. Chemistry and biochemistry
D. Structure and function
E. Diversity
F. Genetics
G. Molecular biology
H. Evolution
I. Ecology
J. Applications
K. Behavior
L. Scientific methods

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1842	Chambers	416	-	-	100	-	-	-	-	-	-	-	-
1900	Parker	419	-	-	-	96.7	-	-	0.5	-	-	-	-
1906	Jordan	312	2	-	34.9	39	-	-	14.4	5	6.2	7.1	-
1916	Gager	620	9.7	-	23.2	47.4	4.4	-	14.3	3.5	5.2	-	-
1929	Geisen	280	20	-	37.2	-	16.4	-	10	-	4.3	8.2	-
1930	Barrows	360	5	-	38.3	16.7	10	-	26.4	-	-		
1932	Haupt	387	3.1	-	55	26.8	8.6	-	14.9	12.8	6.8	-	-
1933	Curtis	534	5	-	25.6	47	8.2	-	11.4	-	-	-	-
1934	Shull	387	12.9	2.3	37.8	7.8	6.3	-	19.3	6.9	-	-	6.6
1940	Stanford	886	2.7	2.5	20.3	19.5	16.9	-	6.7	2	18.7	-	3.5
1943	MacDougall	870	3.3	-	30.8	42.2	5.1	-	5.3	2.2	3.6	-	1.5

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1949	Stauffer	672	1.8	-	64.6	-	4.4	-	14.7	12.6	14.4	2.6	-
1950	Moment	650	8.5	3.8	44.3	18.8	5.1	-	12.7	2.5	2	-	1.2
1952	Etkin	755	2.5	3.2	37	20.8	6.9	0.1	11.3	5.7	6.6	2.8	3.5
1952	Gardiner	630	3.3	7.3	63.5	7.9	4.2	-	5.7	3.6	-	-	3.5
1955	Hall	479	7.1	11.9	34.5	33.2	2.7	-	6.7	5.0	4.8	-	-
1957	Villee	597	6.2	1.8	41.8	7.5	7.9	-	11.5	20.1	-	-	1
1958	Graubard	605	6.7	15.2	47.3	3.7	8.3	-	6.9	4.5	2.9	-	-
1958	Whaley	834	5.8	5.2	35.5	19.3	7.3	-	3.9	3.9	2	3.6	1.4
1961	Core	518	4.4	10	28.2	40.9	7.5	-	3.6	5.9	3	-	1
1962	Goodnight	425	-	4.2	32.9	37	4.9	0.2	5.2	5.4	6.8	-	-
1964	Dillon	802	8.3	1.9	36.5	29.9	10.7	-	2.5	7.6	-	-	1.1
1965	Milne	637	7.1	5.8	23.5	24.8	3.3	1.9	3.1	15.4	13.5	-	1.6
1965	Nason	776	7.6	20.4	34.4	11.4	9.4	-	9.3	-	-	-	-
1965	Simpson	837	7.6	9.2	21.2	14.1	3.8	3.6	18.5	19.1	2.4	1.7	4.3

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1966	Johnson	758	5.7	6.7	34.5	27.3	6.1	3.7	7.4	3	-	-	-
1966	Mavor	681	8.2	2.1	31.1	36.3	3.2	1.8	7.8	3.4	-	-	1
1967	Keeton	917	8.9	8.5	37.7	16.6	4.6	4.6	7.1	6.1	-	5.0	0.8
1967	Platt	510	7.1	8.2	30.9	24.3	3.1	2.7	7.5	13.3	1.4	-	1.2
1968	Curtis	808	6.9	8.2	33.7	16.4	7.9	7.8	7.5	11.6	-	7.3	-
1969	Winchester	687	5.1	12.5	24.8	37.3	4.5	2.1	4.1	-	2.0	1.0	1.9
1971	Baker	890	6.9	15.7	22.5	35.4	3.3	6.4	3.8	3.9	-	7.1	-
1971	Villee	970	9.2	7.0	33.2	15.9	5.5	5.1	3.2	9.9	-	5.7	-
1971	Roberts	602	12.1	8.8	47.2	-	5.1	5.8	10.0	4.2	-	3.7	-
1973	Ebert	735	4.6	11.3	33.2	26.5	5.7	-	2.0	3.5	-	2.0	-
1973	Moment	706	3.4	4.2	37.1	31	4.8	1.3	5.8	6.5	-	2.8	3.3
1973	Orians	621	7.4	26.7	12.2	11.1	6.6	5.3	7.2	11.3	-	4.7	-
1977	Kormondy	463	6.5	5.0	44.9	-	5.3	-	14.9	11.2	-	6.7	-
1979	Arms	936	4.4	7.7	31.6	17.5	3.8	5.1	12.5	11.3	2.0	2.5	1.5

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1979	Jensen	630	5.4	8.1	38.2	13.3	6.8	2.5	10.3	5.9	-	4.0	1.3
1979	Curtis	971	4.5	13.3	28.4	15.4	7.0	6.2	8.4	7.7	-	4.5	-
1982	Weisz	937	6.5	12.4	16.1	16.4	3.3	5.2	10.2	6.4	9.5	4.3	1.9
1983	Guttman	907	8.8	14.6	30.8	9.8	7.5	5.7	8.0	8.4	-	3.9	2.2
1983	Purves	1121	10.0	13.9	30.2	14.1	2.6	7.5	5.6	11.3	-	4.7	-
1985	Villee	1157	4.6	8.6	37.7	15.9	5.1	6.5	5.8	4.4	1.7	2.5	-
1986	Davis	823	10.4	10.3	40.6	11.4	2.9	6.9	4.7	5.3	3.2	3.5	2.8
1986	Raven	1195	7.2	9.8	26.6	20	6.9	2.3	12.1	7.9	3.4	1.9	1.2
1988	Wessells	1239	2.3	6.1	35.6	16.8	5.1	8.0	7.4	7.4	-	3.6	-
1989	Curtis	1178	6.4	11.6	29.6	7.5	5.9	8.6	10.6	7.8	-	-	1.7
1990	Campbell	1161	9.6	6.0	28.5	14.5	5.0	8.0	8.5	8.0	-	2.0	-
1993	Keeton	1194	10.6	10.0	32.2	17.9	3.4	8.1	10.4	6.6	-	2.5	0.8
1995	Purves	1193	8.7	9.9	35.4	17	2.3	7.8	4.3	10.0	3.0	-	1.5
1996	Mader	906	7.9	9.9	32.7	16.6	5.3	6.6	9.5	5.7	1.7	1.5	2.2

Table 5. Subject Content of Textbooks, (b) High school - Grade 12. For each textbook, identified by author and year below, the total number of pages (A) and the percentage of the book devoted to each topic (B-L) is listed.

A. Total pages
B. Cell
C. Chemistry and biochemistry
D. Structure and function
E. Diversity
F. Genetics
G. Molecular biology
H. Evolution
I. Ecology
J. Applications
K. Behavior
L. Scientific methods

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1870	Dawson	246	-	-	8.0	80.9	-		-	-	-	-	-
1889	Wright	290	-	-	-	86.8	-	-	10	-	-	-	-
1896	Bessey	340	10.3	-	31.5	50.3	-	-	-	-	-	-	-
1897	Spotton	216	-	-	1.9	52.9	-	-	-	-	-	-	-
1900	Parker	419	4.1	-	26.0	66.6	-	-	-	-	-	-	-
1906	Bergen	520	1	-	32.9	46.2	2.7	-	2.7	10.2	3.8	5.7	-
1927	Menge	513	-	1.9	17.5	39.9	1	-	1.7	-	22.4	-	6.6
1949	Mavor	393	7.6	-	27.7	33.1	5.1	-	13	3.8	9.2	-	6.1
1951	Woodruff	659	4.4	2.3	34.3	23.5	6.5	-	17.6	0.9	6.2	-	8.8
1957	Brimble	545	2.9	8.1	45.8	15.1	1.6	-	3.9	7.2	10.8	-	-
1959	Smith	652	3.5	12.4	28.3	24.8	13.5	-	-	2.6	16.9	3	-

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1963	Wheeler	672	9.9	-	29.2	44	3.0	-	7.3	5.2	1.5	-	-
1963	Moore	724	9.5	8.6	22.5	17.1	7.9	3.4	13.8	4.3	13.0	8.0	4.2
1965	Miller	660	10.6	-	33.5	26.2	4.1	-	4.9	8.5	8.8	0.8	-
1965	Penny	880	13.9	13.9	39.6	9.9	5.6	0.6	6.9	5.4	-	-	1.9
1965	Otto	743	6.1	7.7	23.7	34.7	7.3	4.0	3.8	6.9	6.7	-	-
1966	Gailbraith	712	11.5	11.7	43.3	4.23	5.1	-	7.4	9.1	-	-	-
1968	McElroy	723	[illegible]	10.7	57.0	9.1	5.1	-	7.4	9.1	2.2	-	2.1
1968	Smallwood	720	3.5	6.7	29.4	16.1	6.9	4.4	17.6	2.8	-	8.0	4.2
1969	Bailey	378	16.4	16.1	6.9	13.0	5.0	1.6	7.1	3.4	3.4	-	-
1973	Otto	824	4.7	7.2	24.8	37	4.2	3.5	5.1	8.1	5.2	-	2.1
1982	Otto	717	3.3	7.3	24.4	38.0	5.0	2.8	3.9	7.0	6.4	-	1.4
1990	Schraer	723	4.8	11.3	36	17.7	3.2	3.6	7.1	4.8	3.2	4.0	2.1

Table 5. Subject Content of Textbooks, (c) High school - Grade 10. For each textbook, identified by author and year below, the total number of pages (A) and the percentage of the book devoted to each topic (B-L) is listed.

A. Total pages
B. Cell
C. Chemistry and biochemistry
D. Structure and function
E. Diversity
F. Genetics
G. Molecular biology
H. Evolution
I. Ecology
J. Applications
K. Behavior
L. Scientific methods

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1901	Aiken	239	-	-	39.3	25.1	-	-	-	-		-	-
1901	James	203	-	-	30.0	-	-	-	1.0	-	69.5	-	-
1908	Bailey	204	-	-	80.9	13.7	-	-	1.5	2.0	2.4	-	-
1909	Brittain	318	3.8	14.2	11.6	5.9	-	-	-	2.2	48.1	-	-
1910	Knight		-	-	-	-	-	-	-	-	100	-	-
1928	Calvert	333	-	-	-	86.8	-	-	-	-	10.2	-	-
1930	Peabody	356	-	-	45.9	5.6	-	-	-	-	45.5	-	-
1932	Meier	446	2	2.7	11.2	41	4.7	-	0.7	0.9	33.9	-	-
1936	Cosens	210	-	-	44.1	46	-	-	-	5.7	14.3	-	2.9
1949	Curtis	572	-	-	14.3	9.8	5.6	-	8.2	3.7	44.4	12.6	7
1959	Smith	652	3.5	7.8	18.8	40.2	15.2	-	2.6	8.7	7.2	-	-

Year	Author	A.	B(%)	C(%)	D(%)	E(%)	F(%)	G(%)	H(%)	I(%)	J(%)	K(%)	L(%)
1965	Miller	660	7.3	1.8	25.6	36.7	1.5	-	4.8	5.9	14.2	-	2.1
1966	Fitzpatrick	398	2.7	-	18.3	36.8	2.3	-		5.3	8.8	-	1.5
1966	Smith	696	5.2	2.3	31.1	19.6	10.3	-	9.8	5.9	11.5	-	-
1968	Miller	775	3.6	4.5	17.5	14.0	6.2	2	8.5	33.8	5.3	5.2	-
1971	Oxenhorn	578	4.3	5.5	51.8	3.8	7.8	2.1	5.2	6.2	17.6	2.6	7.8
1971	Weinberg	618	5.3	11.3	26.8	9	4.2	4.9	12.8	3.4	16.7	5.5	1.6
1980	Balconi	772	9.7	6.4	36.6	22.4	3.4	3.1	-	13.1	-	-	3.6
1991	Aikenhead	239	-	11.3	21.8	-	-	-	-	-	14.6	-	46.9

Table 6. Summary of topics covered in university textbooks over time periods. (a) Covering a variety of subjects. The letters give the topic covered. Column A represents the number of pages. Columns B to K represent the percentage of the book discussing each topic. Standard deviation calculated for all books published in the time period is given in brackets.

A. Total pages
B. Cell
C. Chemistry and biochemistry
D. Structure and function
E. Diversity
F. Genetics
G. Molecular biology
H. Evolution
I. Ecology
J. Applications
K. Behavior

Time	A.	B.	C.	D.	E.	F.	G.	H.	I.	J.	K.
1900-1919	450(156)	6(4)	-	19(17)	61(31)	1(2)	-	10(8)	3(2)	4(3)	-
1920-1939	417(79)	7(4)	1(1)	39(12)	25(17)	8(1)	-	18(6)	3(6)	3(6)	3(3)
1940-1959	698(134)	5(2)	5(5)	44(12)	18(14)	6(2)	1(.5)	9(3)	7(5)	4(4)	1(1)
1960-1979	723(159)	7(3)	10(6)	31(9)	21(11)	5(2)	3(2)	7(4)	7(5)	1(3)	3(2)
1980-1995	1044(214)	7(3)	10(3	32(7)	15(4)	5(2)	7(2)	9(3)	7(2)	1(2)	3(2)

Table 6. Summary of topics covered in university textbooks over time periods. (b) Covering a summary of topics. The category, organisms includes diversity of organisms and physiology and principles includes cell biology, biochemistry, molecular biology, genetics, evolution and ecology.

Period	Organisms	Principles	Applications
1900-1919	73(2)	16(22)	4(3)
1920-1939	64(16)	38(10)	3(3)
1940-1959	61(9)	32(9)	5(4)
1960-1979	54(11)	39(11)	1(1)
1980-1995	47(9)	45(7)	3(1)

Table 7. Summary of topics covered in textbooks over three time periods. The category, organisms includes diversity of organisms and physiology and principles includes cell biology, biochemistry, molecular biology, genetics, evolution and ecology.

(a) University textbooks

Time period	Organism	Principles	Applications
Before 1910	90(3)	0	2(2)
1910 1960	60(9)	34(9)	4(4)
1960-1995	51(11)	41(9)	2(2)

(b) Grade 12 textbooks

Time period	Organism	Principles	Applications
Before 1910	88(8)	6(6)	1(1)
1910-1960	58(3)	25(16)	17(17)
1960-1995	53(14)	38(8)	4(4)

(c) Grade 10 textbooks

Time period	Organism	Principles	Applications
Before 1910	98(4)	2(2)	1(2)
1910-1960	60(20)	15(13)	24(17)
1960-1995	45(15)	33(21)	16(19)

Appendix 3, Continued

Textbooks Analysed for Content

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