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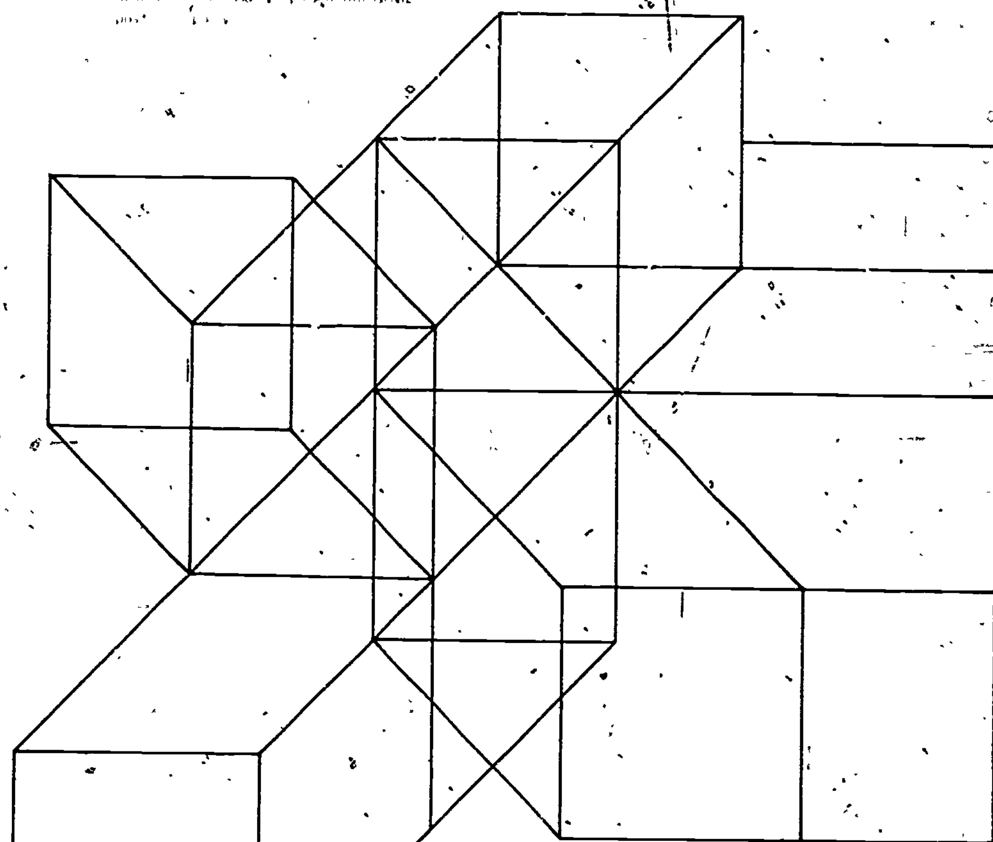
ABSTRACT

One of the goals of science education is to foster critical and scientific thinking skills. However, if the meaning of the terms "thinking critically" or "thinking scientifically" is not clear, these phrases will become vacuous slogans beyond translation in teaching methods and curriculum materials. Therefore, the fundamental aspect of these terms must be embraced in the discourse of science teaching itself. Since science knowledge is growing in a way that makes it imperative for everyone to know how to handle knowledge itself, the task of getting clear about scientific thinking is imperative. Suggesting that scientific thinking (or critical thinking in science) is more than puzzle-solving and logic-wielding and avoiding a detailed philosophical and psychological treatise on the nature of thinking, some examples of what appears to pass for thinking are presented. These examples show that conventional ways of talking about "thinking" in science education are inadequate to the task of showing what students have to know as base to think scientifically. The nature of scientific knowledge is then considered to build some ideas about what it means to hold scientific knowledge, the essential points illustrated with extracts from science teaching. Implications and recommendations for science instruction are considered. (Author/JN)

Science Council of Canada

What is Scientific Thinking?

A Discussion Paper
by Hugh Munby



Discussion Paper D82/1

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March 1982

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FOREWORD

This paper is the fourth in a series of discussion papers prepared for a study of Canadian science education being undertaken by the Science Council of Canada, under the direction of its Science and Education Committee. The study, which began in the spring of 1980, has three overall aims:

- to establish a documented basis for describing the present purposes and general characteristics of science teaching in Canadian schools;
- to conduct an historical analysis of science education in Canada;
- to stimulate active deliberation concerning future options for science education.

As this third aim suggests, the Science Council has, at present, no collective view on desirable directions for science education in Canada. However, in order to develop such a view, it is actively soliciting a diversity of opinions. It is intended that these viewpoints, expressed in the form of discussion papers and disseminated as widely as possible, will prompt science educators and others to review current policies and practices. By sharing in these deliberations and at the same time conducting a systematic inquiry into current and past policies and practices, the Science Council hopes to acquire a good understanding of the state and needs of science education in this country, and thereby make constructive recommendations.

Earlier papers in this series have stressed the importance of certain objectives for science education which, it has been claimed, are absent from programs in Canadian schools. James Page, in A Canadian Context for Science Education, focused on the potential of science courses to contribute to improved national awareness. Glen Aikenhead, by contrast, thought science should be taught in such a way that students learn about its relevance and limitations in regard to social and political problems. The third paper, An Engineer's View of Science Education, by Donald George, suggests that the intellectual processes of the engineer should be considered at least as important as those of the scientist when the objectives of science teaching are being formulated.

This paper takes a somewhat different approach; it re-examines an objective long considered by science teachers to be important. Hugh Munby, an experienced teacher and teacher educator, takes a fresh look at what it means to try to get students to think critically and scientifically. Illustrating his argument liberally with transcribed excerpts from actual instances of teaching, he argues a case for what he calls "intellectual independence" as an important aim for all science teaching.

It must be stressed that the views expressed in this discussion paper are those of the author, and not necessarily those of the Science Council or its Science and Education Committee. However, in publishing the paper, Council believes that a well-argued position has been set out, and that discussion amongst a wider audience can benefit both the study and Canadian science education, in general.

James M. Gilmour,
Director of Research,
Science Council of Canada

INTRODUCTION

Although I am an avid collector of lesson tapes and transcripts, I have no such precise records of my own performance as a high school science teacher. Yet, I vividly remember one piece of my teaching. There I was, a newly arrived immigrant to Canada, a novice teacher in every sense, about to begin one of my first chemistry classes. Oh, I was a science teacher, all right; I sported a freshly laundered lab coat and stood resolutely behind the teacher's laboratory bench. I possessed the signs of authority and the security these offer their owner but, more than that, as an officially certified science teacher I believed I really knew what was what in the material world. Almost as if this pomposity was not enough, I announced dramatically, and in my thickest British accent, "Even if you learn nothing else in this class, at least you will learn how to think," (or something like that). I then launched into orbitals and atomic structure, leaving everyone else in the room far behind. Perhaps what is most irksome about this distressingly permanent memory is that I came soon afterwards to realize that I hadn't the faintest idea of what I meant by "learning to think" or by "thinking."

Thinking - and I know I shouldn't say this - thinking ought to be on every educator's mind. Indeed, if we all scrupulously followed the slogan-like aims of education promulgated by every school board in the country, we would be up to our necks trying to get our students to "think." Punning aside, we recognize the gravity of the challenge to get our students to think, to think critically, and even to think scientifically. Certainly it is abundantly clear to me that science education fails if it doesn't tackle the matter of thinking.

However, if we don't get a firm grip on what we mean by "thinking critically" or "thinking scientifically," these phrases will become vacuous slogans quite beyond translation into teaching methods and curriculum materials. In my view, we have enough educational slogans and, because I judge "scientific thinking" and "critical thinking" too important to be cast around offhandedly, I will argue how a very fundamental and specific aspect of these terms can and must be embraced in the discourse of science teaching itself.

I shall begin by showing how urgent is the task of getting clear about scientific thinking. Simply, knowledge in science is growing in a way that makes it imperative for everyone to know how to handle knowledge itself. I will then turn to a general theme of this paper: there is much more to scientific thinking (or critical thinking in science) than puzzle-solving and logic-wielding. Here, I will purposefully avoid a detailed philosophical and psychological treatise on the nature of thinking and, instead, concentrate on some straightforward examples of what seems to pass for thinking. These examples show that our conventional ways of talking about "thinking" in science education are inadequate to the task of showing us what, fundamentally, students have to know at base in order to think scientifically.

Next, we need to consider what scientific knowledge is all about. On this, we can build some ideas about what it means to hold scientific knowledge, the essential points being illustrated with extracts from science teaching. This leads us to see what has to be provided in science teaching so we can be sure that youngsters have at least the chance to think scientifically.

Because I understand that one purpose of a paper like this is to promote discussion, I will end with a number of possible discussion points from the topics I cover. My hope is that these, together with some practical investigations and suggestions, will not limit discussion, but will lead to spirited interchanges.

II THE KNOWLEDGE EXPLOSION, A PROBLEM FOR TEACHERS AND STUDENTS ALIKE

If the seventies are remembered for anything, they should be remembered for how they confronted us with deep and seemingly intransigent problems: the poisoning of ourselves and our environment, the ethics of genetic engineering, the certain depletion of fossil fuels, the uncertain promise of nuclear energy, and the "knowledge explosion." All are science-related and demand thoughtful solutions by a populace which can make sense of scientific information and judge it. But, for my money, the problem that weighs most heavily on the shoulders of science teachers and curriculum developers at all levels of education is the so-called knowledge explosion.

Personally, I have a distaste for using phrases like "knowledge explosion" without getting some fix on the extent of the problem apparently conveyed by the expression. So, with the expert help of a research librarian at Queen's University, I attempted to gauge the extent of the growth. The findings were sobering. For instance:

- The total number of documents cited in *Chemical Abstracts* grew from 239 687 in 1967 to 306 906 in 1980.
- In 1927, *Biological Abstracts* cited 14 506 documents; the estimate for 1980 was 162 500.
- The subject of "Quantum Mechanics" in *Chemical Abstracts*, which elicited 634 papers in 1967, had burgeoned to an estimated 1180 papers in 1980.
- There are between 8 to 10 million pages of printed matter on science and technology topics added annually to our collected stock, according to a member of the USSR Academy of Sciences.

I really have no idea how science teachers are meant to cope with all this information and keep sufficiently alert to developments in their subject so that they can offer contemporary knowledge to students. It is equally staggering to contemplate the additional amount of information that our high school and university graduates will face during the course of their adult and professional lives. How will they cope? The typical way of addressing this problem is to suggest that we need to get students to think critically about scientific information so that they can deal with it intelligently. I agree wholeheartedly, but I don't agree that our usual ways of construing critical or scientific thinking are going to be helpful. They may be downright misleading.

III TAKING A LOOK AT THINKING

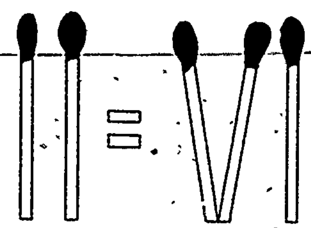
What we mean by "thinking" is ambiguous and obscure. Traditionally, the term "thinking" has been used to embrace a wide variety of mental processes, from the meanderings of the mind while we walk along the street, to the more disciplined mental activities we believe we engage in when we play chess, argue with our colleagues, and teach. Because it is not possible to provide a broadly satisfying definition of "thinking" in this paper, I will provide a few examples of the term's use. From these at least we might uncover a sense of what we think we do when we think.

Dead Philosophers and Other Puzzles

> A ship is twice as old as its boiler was when the ship was as old as the boiler is. The sum of their ages equals 49 years. How old is the ship and how old is the boiler?

Puzzles like this are intriguing. They take a bit of work; yet we can solve them once we have hit upon the right way to use the rules and algorithms. In some puzzles the rules are less than obvious. In cryptic crossword puzzles, for example, there are rules. "A superior helper" in seven letters is "abettor," but what rules are used to solve "unearthed former philosopher at start of day"?

Sticking to rules, then, is a feature of thinking, but sticking to rules overzealously can cause difficulties when puzzles or problems require "breaking set." For instance: "There is three errers in this sentence." Can you find them? And, in the figure below, move just one match so that the left-hand side of the equation equals the right. (There are two quite different solutions.)



One might object that puzzles like these don't arise in science teaching. But they do. We all know that getting youngsters to balance chemical equations, compute the current through a simple circuit, determine the velocity of a frictionless vehicle on an inclined plane, and so forth, are part and parcel of the business of teaching science. For instance, take the following segment from the beginning of a grade 13 lesson*:

Teacher: $1s^2\ 2s^2\ 2p^5$. And what will that be?

Michael: Fluorine?

Teacher: That would be the fluorine atom, eh? And so the fluorine ion?

(There is a pause followed by a few indistinct mumblings.)

Betty: Six.

Teacher: Six. Neon? Betty, since you are doing so well...

(The lesson continues.)

* The names have been changed, but actual transcripts are used in this paper.

Puzzle-solving, if you will, is certainly one aspect of thinking, although the concept of thinking is broader.

Tests of Thinking in General

The scope of what might be meant by "thinking" is evident in the vast quantity of test materials that have been developed with the specific intent of measuring aspects of thinking ability. The following two items appear in the Canadian version of a widely used intelligence test:

> Cause and effect, means and ends, seed and ______________ cannot be severed.
>
> (A) caution (B) thought (C) fruit (D) science
> (E) philosophy

> A table model radio set is made to sell for $29.75. The dealer's cost is 60 per cent of the established selling price. What is the dealer's gross profit per set?
>
> (A) $17.85 (B) $48.58 (C) $11.90 (D) $48.65
> (E) None of these

These items lean heavily upon concepts and vocabulary. True, one cannot answer the second item correctly without some ability to manipulate numbers, but success demands a comprehension of the interrelationships of the concepts "cost," "gross profit," and "selling price." It is this sort of understanding of relationships among concepts which is tested, along with other things, in the Miller Analogies Test. The following example is not untypical and plainly shows how difficult it is to generate test items that are free of cultural or other bias. Imagine an immigrant struggling with this one:

> Palm: Atlantic :: Beach ______________
>
> (A) Pacific (B) Shrub (C) City (D) Tree

There are, of course, many variants of this type of testing, and a legitimate complaint might be that items of this sort fail to tap our abilities to pierce arguments for their flaws and strengths. To some, these abilities are the constituents of critical thinking, and they are well represented in tests bearing that name. The Watson-Glaser Test of Critical Thinking has subtests designed to measure inference, recognition of assumptions, deductions, interpretation, and evaluation of arguments. In the following item, for example, we are asked to judge if the conclusions do or do not follow:

> A report of the US census states that during 1940 there were approximately 1 656 000 marriages and 264 000 divorces granted.
>
> Conclusions:
> (A) Getting a divorce is a quick and easy matter in the United States.
> (B) If the above ratio still holds true, then about six times as many people get married each year as get divorced.
> (C) The divorce rate in the US is much too high.

In another test, we are asked to determine if there is sufficient or insufficient information for the conclusion given:

> A student places two pieces of bread in separate sealed containers. The one is placed in sunlight, the other darkness. After four days, there is mould on the piece of bread placed in sunlight, but no mould on the bread that is in the dark.
>
> Conclusion: Mould needs light to grow.

Actually, it is probably unfair to put this item, which comes from a test that professes to measure science attitudes, so close to one on critical thinking. However, the similarity between the two is pronounced. As evident, the content is scientific, but beneath that, and not buried very deeply, is a straightforward commonsense argument which can be unpicked with straightforward commonsense reasoning. After all, there is nothing particularly scientific about the idea of comparing things in a way that will reduce the possible interference of other factors. This may sound a little strange, for we seem to be edging towards the view that there may be nothing special about scientific reasoning that warrants setting it aside from other sorts of reasoning.

One might even feel that much of what we believe critical thinking in science to be is straightforward puzzle-solving and logic-wielding.

Standard Interpretations of Thinking in Science

Discussions of science curricula frequently refer to the distinction between "science content" and "science process." So far as I can gather, "science content" refers to such things as theories, findings, and the like which, in my schooldays, seemed to be the entire compass of the science curriculum. "Science content" then embraced the properties of sulphur, the atomic theory (or at least one version of it), laws of friction, cell theory, and much, much more. "Science process" is a term applied to what it is thought that scientists do (or did) to generate this vast array of science content. Scientists, we gather, observe carefully, generate and test hypotheses, control variables, retain a staunch allegiance to evidence (rather than to what others might say), and are always prepared to jettison a theory if it fails to serve its purpose. Some of this gets packaged in the familiar wrapping of the "scientific method." Sometimes, the disposition to behave in a way that mimics the ideal scientist gets christened a "scientific attitude." We don't have to look very far to find interpretations of "science process" manifested in test items. For example, here are two selected rather arbitrarily from different tests of science processes:

1) Several similar rosebuds were selected for an experiment. Half the buds were placed in a litre of tap water; the other half were placed in a litre of similar tap water in which aspirin had been dissolved. The most general hypothesis the experiment was designed to test was that aspirin

(A) will purify tap water.
(B) has an effect on rosebuds.
(C) improves the appearance of rosebuds.
(D) has the same effect on water as do rosebuds.

2) In order to prove that "Not all things get bigger as you heat them," which of the following would you need to do?

(A) Find one thing that does not get bigger when it is heated.

(B) Find all the things that do get bigger when it is heated.
(C) Find one thing that gets bigger when it is heated.
(D) Find all the things that get bigger when they are heated.
(E) Find all the things that do not change size when they are heated.

This picture of scientific process or scientific thinking is surprising and tempts one to think that all is well here, especially since the phrase "scientific process" is still very much a part of the science educator's language, even though it gets transformed into such phrases as "scientific attitudes" or "inquiry skills" from one curriculum to another. But that would be a mistaken conclusion. All is not well. A recent research paper on critical thinking illustrates this when it lists a number of fallacies allegedly relevant to the study of inquiry in biology.[1] Among them:

- Assuming that events that follow others are caused by them.
- Drawing conclusions on the basis of nonrepresentative instances.
- Drawing conclusions on the basis of very small and fortuitous differences.

Of course, these fallacies are not the exclusive property of faulty reasoning in science. Errors of this sort can be made by lawyers, historians and investors, to name a few. In fact, there is nothing peculiarly biological about the list at all, for the fallacies are tied to rules of reasoning that are not dependent upon context.

To a very large extent, we have reached the same conclusion here as we did previously, though this time the conclusion was arrived at by examining some examples drawn from the field of science education. There is no longer merely a suspicion here, but a pronounced disquiet,

1. A. Dreyfus and E. Jungwirth, "Students' Perception of the Logical Structure of Curricular as Compared with Everyday Contexts: A Study of Critical Thinking Skills," Science Education, vol. 64, no. 3, pp. 309-321.

for critical thinking looks a lot like the "science process" sort of thinking. Both seem to be varieties of puzzle-solving or logic-wielding.

Actually, when you think about it, there is no reason why the discipline of science should have a monopoly in the critical-thinking market. A detailed study of the letters of Benjamin Disraeli is no less reliant upon systematic and critical thinking than is a thorough investigation of recognition behaviours among fishes. The fact that political theory and ichthyology employ different techniques to investigate different aspects of life provides no grounds for saying that one leans more heavily upon critical thinking than the other. Science, the argument might continue, is as dependent upon critical thinking as are literature, history, and musicology.

The inescapable conclusion so far is that we have exhumed nothing from these conventional ways of talking about thinking that is distinctively scientific. All that we have seen applies equally to other areas of the curriculum. But, before we abandon the view that science education has no particular claim on teaching youngsters to think critically, we need to step back. There must be something distinctive about thinking in science, otherwise science would not stand as a separate discipline.

A Radically Different Approach to Thinking of Scientific Thinking

Looking back on it all, I am astonished that as science educators we have been seduced into believing that thinking in science simply involves puzzle-solving, logic-wielding, and a dash of "scientific method," whatever that might be. It is ironic that we have uncritically adopted for "scientific thinking" a version of "critical thinking." But although puzzle-solving and logic-wielding do not help us distinguish "scientific thinking" from disciplined thinking generally, we must not forsake the quest for what is unique about "scientific thinking." Accordingly, I propose to approach the topic from a startlingly different (though not original) viewpoint. We must begin by looking at what scientific knowledge is all about.

The clearest way to illustrate something of the basis of scientific knowledge is to share another piece of classroom discussion. The following extract is from a grade 4 science lesson. The teacher has been introducing a classification system and has arrived at a distinction between living and nonliving things. The next distinction is just ahead.

Teacher: Now, we are going to leave the nonliving things for later and study just the living things.

(Writes "living" on the board)

... Now, let's divide all the living things into two divisions. Into what two divisions can we divide every living thing? Every living thing is either a ______ or a ______? Lucy, give me one division.

Lucy: People?

Teacher: People are just part of one of the two divisions.

Peter: Plants and animals.

Teacher: Good for you, Peter. That's right. Every living thing in this world is either plant or animal. People, Lucy, are animals, so they fit in this division.

Lucy: People aren't animals, they're humans.

Teacher: People are animals, the same as dogs and cats and so on.

(Much laughter, and several loud objections by a large number of children speaking simultaneously. It appears that they disagree with this last statement.)

... People are animals. What's wrong with that? They're not plants, are they?

Jimmy: But people talk, and have two legs and arms, and move and can think. Animals aren't like that.

(Laughter)

Teacher: People do think, and this makes them one of the highest forms of animals, but they are still animals. . . And other animals communicate with one another.

(Several children are noisy and visibly disturbed)

. . . That's enough. People are animals. Now maybe it would help if we looked at the differences between plants and animals. What are the differences? There are at least three that you could name.

(And the lesson continues.)

Quite obviously, something is going wrong in this lesson. Lucy's contention that people aren't animals is at odds with the teacher's declaration that they are. Of course, there may be many possible cogent explanations of Lucy's emphatic rejection of the teacher's statement, but no satisfactory explanation can be built on the grounds that either Lucy or the teacher is somehow deficient in logic-wielding or puzzle-solving. Some other explanation is called for. I believe the most coherent explanation focuses on language and knowledge.

In Lucy's world, we can imagine, conceptual distinctions have been made between people and animals because it is important to make these distinctions. (Why else would we make distinctions unless they were important to us?) For Lucy, then, people are not animals; their features and habits are different of course, but, more significantly, members of the two sets occupy distinctive positions, probably by virtue of the different relationships she perceives that they have to her. None of this is surprising; indeed, Jimmy appears able to articulate some of the differences that are evident to him in his world. This is quite acceptable, for in our everyday use of language around the home, farm, and streets we wield the conceptual distinctions in precisely the way that Lucy and Jimmy do. Why, then, is Lucy so persistent in pressing her viewpoint?

Perhaps Lucy just has trouble with scientific terminology; but that explanation doesn't push the matter far enough. The essence of the disagreement is that neither party apparently understands that the concept "animal" is just that, a concept. Further, neither seems to see that the word "animal" is part of two classification systems, or taxonomies: a scientific one, and an "everyday" one. The elements of such systems, which we invent, do not necessarily exhibit unique relationships with what we come across in the world. Indeed, because we construct them for different purposes, it is likely that different taxonomies will give different meanings to specific words. Lucy's taxonomy sorts out her world, and the teacher's taxonomy sorts out the world according to how science sees it. So, both Lucy and the teacher are right, though unknowingly they are each using one part of two taxonomies for different purposes.

In this we see something very fundamental about scientific thinking: it is a human invention which involves using language to paint the perceptual world in a very particular and disciplined fashion. This is the foundation upon which the radically different approach to viewing "scientific thinking" is to be erected.

IV SOMETHING ON THE NATURE OF SCIENTIFIC KNOWLEDGE

Scientific knowledge is a very specific and disciplined way of constructing the world. According to this view, which we can term "constructionist," we construct our own realities. Some of these realities are widely public; these are the disciplines. In any discipline reality is constructed out of a network of concepts, principles, explanations and theories, which are all human inventions. The sorts of "constructs" that are used, the ways in which they are developed and tested, and the purpose they serve distinguish the disciplines one from another.

The purpose of science is to construct generalized models to explain and predict natural phenomena. The constructions should match data consistently; frequently they must be precisely formulated (often mathematically). And the concepts are meant to be free of willful behaviour. Other disciplines will show differences: history does not strive for claims about human action that can be generalized but for detailed explanations of particular actions. Art constructs a world differently again. As disciplines evolve, so the rules change. Yet disciplines are rule-bound, and thus yield public knowledge which is as strikingly different from private knowledge as Lucy's knowledge is different from her teacher's.

This view of knowledge in science comes from philosophy. A very readable and far fuller account is available in Stephen Toulmin's *The*

Philosophy of Science. For present purposes, his arguments can be set aside and replaced by some thoughts on what this "constructionist" view of scientific knowledge implies.

Are There Really Black Holes? or, "How could you ever tell anybody if you happened into one?"

For me, the most tantalizing concept in contemporary astronomy is the black hole. To some, I am sure, it is deeply puzzling to think that there are "objects" in space which can never be seen, touched, or sensed, simply because they attract so fiercely that nothing escapes their maw, not even light. How, then, do we know they are there? Now that's an awkward question, largely because it's an inappropriate one: we are not really claiming knowledge of their presence when we say there are black holes. Instead, we are claiming that the only coherent way we can explain certain phenomena is if we invent the concept of black holes having properties that do not violate any of the major components of our present construction of the universe. Science is the creation of human beings.

Our total range of concepts are first and foremost language devices. "Genes," "tachyons," " black holes," and "schizophrenia" are terms that have been invented for the specific purpose of satisfying our need to explain and to predict, and to be able to talk to each other about our explanations and predictions. Of course the better the concepts are, the more "real" they seem. (And, indeed, some can eventually be used to describe real entities.) But the basis of scientific knowledge remains firmly fastened to the idea that we invent our knowledge.

Not only are our concepts formulated by ourselves, but so are our theories, explanations, and principles. So it is that theories and explanations are not, strictly speaking, true or false, right or wrong; rather, they conform or do not conform with our observations, and they are judged on their usefulness to our attempts to construct a predict-able, scientific world about which we can make generalizations. Theories that have fallen into disuse are just that; it's not a matter of their being wrong, it's simply that we have found them to be less useful to us now than they were when they were first developed.

There is an interesting offshoot of the constructionist conception of scientific knowledge which bears directly upon the concerns of science educators. I identify it as the "theories-learned-in-school" syndrome, which appears either in the form of a university student telling a former grade 13 chemistry teacher about discovering that the atomic theory learned in grade 13 was wrong, or in the form of university science teachers complaining that they have to get their first-year students to unlearn all their school chemistry. What seems to have been missed here, by all parties, is that theories or models are not right or wrong but of variable usefulness depending upon the phenomena we wish to explain and the amount of sophistication we wish to build into the model. Presumably, if the constructionist view of knowledge were to prevail, this difficulty at the high school and university interface would be mollified.

If teachers and texts in schools continually made it clear that models and theories of increasing complexity are generated to deal with increasingly diverse and complicated observations, then students entering university would be prepared to anticipate novel and more refined models. If some students are evidently getting the message that part of their high school science is "wrong," then they must have acquired or developed an inadequate and misleading view of scientific knowledge, one that leaves them disadvantaged when it comes to scientific thinking. They can't comprehend the context of scientific knowledge, and are unable to cope with the notion that theories and models change. Imagine trying to tell a youngster that the plum-pudding model of the atom has been supplanted by another, when he or she had no idea as to what went into developing the model in the first place, but learned it in the naive belief that scientists really knew what the atom was like. "Scientists were wrong! My teachers were wrong!" There would be no intellectual engagement, just bewilderment and distrust.

V THE CONTEXT OF SCIENTIFIC KNOWLEDGE: EDUCATION OR INDOCTRINATION?

The constructionist view demands we recognize that the language we use in conveying science to youngsters will determine whether or not they understand scientific knowledge. The crucial point is the context of the language, the significant elements of which are:

1. Knowledge is constructed by people.

2. Theories, principles, explanations, models and postulated entities are constructed by us, and not handed to us by nature.

3. The nature of these constructions is controlled by a set of rules: among these is the determination that the construction fit the data it is intended to deal with.

Out of this flows the necessary and unavoidable implication that science has not the logical commerce with absolute truth people might have thought. Psychologically, it may be very appealing and satisfying to think that science provides a hot-line to reality. But the fact is that it doesn't, even though scientists and others may well find themselves driven zealously by a passion for uncovering absolute truth. This is part of the psychology of science. From a logical point of view, though, the discipline of science strives for something importantly different from absolute truth: it strives for increasingly useful constructions of nature upon which predictions and generalizations can be based. This is not to say that at some point we are not entitled to develop our own thoughtful judgments about the relationships between scientific constructions and reality. Undoubtedly, as we develop intellectually, so we develop more sophisticated beliefs about our own views. But this point is not to be taken as offering aid and comfort to science educators who are committed to the view that science really does tell us what goes on in the perceptual world. On the contrary, the science teacher must be sure to present scientific knowledge in such a way that his or her students can begin to develop an understanding of its basis.

Any teaching that denies students access to what makes science tick automatically limits their opportunity to make a deliberate and fully reasoned judgment about their own beliefs. In the classroom, whatever pre-empts the learner's judgments can only be characterized as miseducational, if not indoctrinaire.

The Importance of Making Context Clear

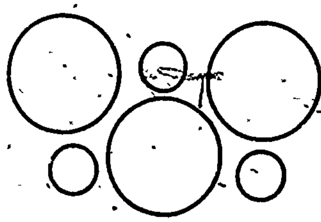
The preceding brief journey into the nature of scientific knowledge demonstrates how important it is to make explicit the context of language used in teaching and in curriculum materials. At base, we need to become accustomed to talking in such a way that a plain distinction is always made between what we have invented (in the way of concepts and theories) and what nature has given us. Without the separation the context of scientific knowledge is lost.

This point is crucial. We can't let it pass without taking a look at a fragment from another lesson, this time grade 9. In a previous extract we saw a striking example of how the meaning of language in science can be so different from that of our everyday conversation. But do youngsters pick up that difference, and so fully possess the fundamentals of scientific and critical thinking, or does it wash over them? You be the judge.

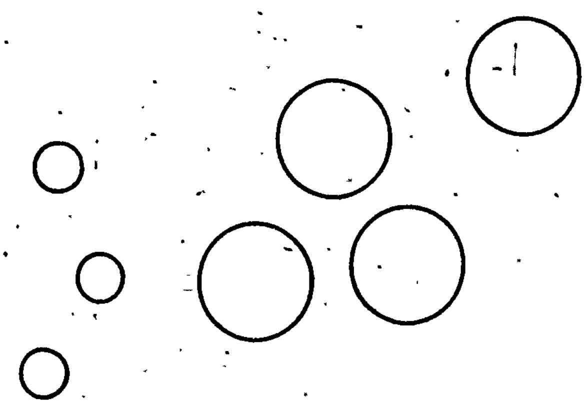
"Heating Mercuric Oxide"

The dialogue occurs after an "experiment" in which samples of mercuric oxide were heated in test tubes by students. Predictably enough, the teacher has managed to get the class to agree that the oxygen which rekindled the glowing splint came from the mercuric oxide. Let's join the discussion.

> Teacher: But how is the oxygen in mercuric oxide? Mercuric oxide doesn't look like oxygen. Mercuric oxide doesn't look like mercury. So how can it have mercury and oxygen inside it? Paul.
>
> Paul: When, er, when you get a solid, all the molecules are tightly attached; when you heated it, it split up.
>
> Teacher: So, what Paul thinks is this. When we have mercuric oxide, we've got molecules of mercury and molecules of oxygen all packed in here tightly like this.
>
> (He draws a diagram.)



> Then when we heat this up, what's going to happen to this, Paul?
>
> Paul: It's going to start breaking up... will start sort of breaking apart.
>
> Teacher: They're going to start breaking apart, and we'll get the molecules of mercury over here, and the molecules of oxygen over here.
>
> (He draws.)



> They'll separate. Does that seem reasonable?

This is fascinating: In one swift step we move to an explanation of chemical change that relies heavily on a familiar language, though the language itself (as we know, but the youngsters may not) carries with it a vast and intricate conceptualization of molecular structure and kinetics. There is nothing in the language that signals to the listeners and participants that it moves between conceptualization and data. These significantly different parts of the discipline of science are here inseparably joined, and all concerned are left with no choice but to think that this "breaking down of a molecule" is what really happens when we heat this orange stuff. (In talking with the teacher, I discovered that the context of scientific knowledge had not been explained in previous instruction either.) We can see how easy it is for the language of the science classroom to thoroughly misrepresent the basis of scientific knowledge.

VI HOLDING SCIENTIFIC KNOWLEDGE

The ability to think critically in science and about science must be firmly based on an understanding of how the English language is used in science and how its context is to be taken as a construction of reality. But it's not enough to let the matter rest here, for there are other essential components to disciplined scientific thinking which contribute to how we hold scientific knowledge. Thus, if we want our students to acquire a facility in scientific and/or critical thinking, these factors should be transmitted to them.

Probably, the reader's initial reaction will be: "Ah, now we get to the part about the five steps of the scientific method." Wrong. Quite frankly, I find the "scientific method" very tiresome. First, the history of science shows that the scientific method does not seem to lead to mind-boggling conceptual novelties. (In fact, we are likely forced to describe such "discoveries" according to a logical step-wise progression simply because it is far easier to follow a tale when it is told like that. An ex post facto explanation of how we solved puzzles similar to those given earlier probably doesn't come close to describing what we might think happened in our heads.) Second, in just the same way that science doesn't have the corner on the critical thinking market, it doesn't have the corner on the scientific method market. Indeed, there is every good reason to think that the monopoly is held elsewhere, in the international corporate giant of all disciplined intellectual inquiry.

I hold that, basic to critical thinking in science (and, I admit, in every intellectual sphere), is the ability to make judgements for oneself. This is a serious undertaking, and must be approached with responsibility and thoughtfulness. As a result, it is necessary to set the notion of making judgements for oneself distinctly apart from other ideas about scientific thinking or critical thinking. This is done by inventing the idea of intellectual independence, which we can define in the following way:

> A person can be said to be intellectually independent when he or she has all the resources necessary for judging the truth of knowledge independently of other people.

Doubtless, professional scientists use this capability when they study research papers. They know the theoretical background to the research, and so can judge whether or not the reported experimental work is apt. Also, they use their understanding of the relationship between evidence and theory, of what constitutes adequate evidence, and of flawless argument, to assess the significance of the research. Of course, for the scientist, a basic part of intellectual independence comes from an understanding of the language of science, both its content and, more importantly, its context.

We can represent on a scale the ways in which people hold scientific knowledge. At one extreme will be those who naively and uncritically accept every piece of scientific knowledge as absolutely true, without giving any thought to the grounds which make that knowledge acceptable to the scientific community. At the other extreme will be those whose understanding of the nature of scientific knowledge permits them to view knowledge as made by us, and whose familiarity with the disciplinary rules of science gives them the wherewithal to make sound and independent judgements about knowledge.

In the face of the quantity of information generated in the discipline, it is obviously desirable to equip all science students, whether they plan to specialize in science or not, with the means for being intellectually independent about science. How can this be done?

Another Look at "Heating Mercuric Oxide"

The focus here again needs to be on teaching, with emphasis on what can be learned because it is provided in the teaching. We can get a good feel for what needs to be present in teaching, if it is to provide intellectual independence, by examining some further extracts from "Heating Mercuric Oxide."

This extract occurs close to the beginning of the lesson. Here students are reporting their observations.

> Teacher: How many other people observed a red stage in here?
>
> (Several hands are raised.)
>
> ... Okay, so I guess those are our observations: a sort of a, a dark, brick red color and then slowly going to black, eh? Jackie.
>
> Jackie: Ours turned from the red to brown . . .
>
> Teacher: Jackie said her test tube turned a kind of brown color as well. It might have been because the test tube was dirty.
>
> Jackie: Just a brown color.
>
> Teacher: Did you notice it in spots around, or was it all that color?
>
> Jackie: It was just spots around.
>
> Teacher: That might be because your test tube might have been a bit dirty. If it had been the whole thing, then maybe, but not that way.
>
> (The teacher proceeds to another point.)

It may well be the case that Jackie's observation fails to coincide with our expectations of the way nature ought to behave, yet the fashion in which it is ruled as irrelevant bears no resemblance to how we operate scientifically. For Jackie, her observation is irrelevant because the teacher said so, and it is plain that she is offered no choice here but to be intellectually dependent upon her teacher for judgements about the worth of her observation.

The next, and last, extract follows shortly after the very first one, in which the circles were drawn. The teacher has just made the point that the mercuric oxide splits up in a way that is quite different from what happens when water is heated and converts to water vapour.

Teacher: Instead of thinking of mercuric oxide as being molecules of oxygen packed closely to molecules of mercury, let's think of mercuric oxide, since it's matter - mercuric oxide's matter. How do we know mercuric oxide is matter? Ruth?

Ruth: All matter is molecules?

Teacher: Well, do we know mercuric oxide is molecules? George.

Ruth: Yes.

Teacher: Have you seen one? How do we know mercuric oxide is matter? George.

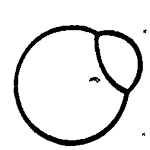
George: Because it has weight and takes up space.

Teacher: Good. Now if mercuric oxide is matter, what's it made up of? Jackie.

Jackie: Molecules.

Teacher: So let's figure out . . .

(Draws the diagram and labels it "Mercuric oxide molecule.")



... We've got a mercuric oxide molecule here. . . That's a mercuric oxide molecule. It's got a bump on it. Can you think what that bump could be?

Richard (quietly): A growth.

Teacher: Linda.

Linda: Oxygen.

Teacher: Well, what's this big part then?

Linda: Mercury.

Teacher: Okay.

(Labels the parts of the diagram "mercury" and "oxygen.")

... Mercury and oxygen what? Mercuric oxide could be made up of mercury and oxygen. But mercury and oxygen what? Stan.

Stan: Molecules?

Teacher: No. There's another possibility. . . . If it isn't made up of molecules, what's it made up of? It . . .

Ann: Atoms.

The teacher then moved to a description of what happens when this "thing" is heated. There was no discussion of the model itself.

Two points are worth making here. First is the absence of any real argument to establish that mercuric oxide is considered to exist as a molecule instead of, say, a form of conglomeration of smaller molecules. Ruth, George, and Jackie who are supplying the "correct" missing links, perhaps sense that their participation serves only to take the teacher along his own agenda. Richard's <u>sotto voce</u> "a growth" seems fitting, and gives rise to the second point: nothing whatsoever is done for the students so they can see that this representation has any validity at all.

There is no attempt to make the model appear plausible by showing how we think it fits the data. Instead, the central model in the teacher's presentation is parachuted into the discussion in such a way that the students are left intellectually dependent upon the teacher for most of the argument. Here, perhaps more clearly than elsewhere, we see that assessing argument (using critical thinking) is not just a matter of wielding logic or solving puzzles. To judge what is available to this grade 9 class, we have to view the argument from a perspective which incorporates an understanding of the nature of scientific knowledge and thinking. From that angle we are obliged to acknowledge that there is little or no opportunity here for youngsters to develop and use intellectual independence. Moreover, the language itself offers a distorted view of how to argue scientifically.

Intellectual Independence

In my collection of science lesson transcripts there are many more examples of teaching that leave youngsters intellectually dependent upon their teacher. For now we can pass over these and, by reflecting on what we have seen, come to list the sorts of moves a teacher has to adopt to encourage intellectual independence. When the following features are present in teaching, we can be assured that something is being done to show how scientific knowledge is appropriately held and handled:

a) Evidence is provided in support of claims.

b) The argument is present.

c) Correspondence of diagram or model to phenomena is demonstrated by argument and by evidence.

d) Adequate reasons are given for accepting or rejecting a student's statement or response.

e) Suggestions, questions, and objections by students are honoured and are treated with regard to reason.

f) There is provision for students to make judgements, by recourse to phenomena, about the viability of models, theories, and explanations.

g) Alternative models, theories, and explanations are provided to permit students to make judgements among them.

h) Discrepancies in observations or evidence are rationally resolved.

Recall also that scientific knowledge is constructed by human beings and, by extension, our theories, principles, explanations, constructions and postulates are too. Our constructs are controlled by rules, among these being the determination that the constructions fit the data.

Teaching and curriculum materials which voice these points clearly provide youngsters with what is fundamental to thinking critically and scientifically.

VII ENDINGS AND BEGINNINGS

It is likely that the points made in this paper may not be acceptable to everyone. So, rather than ending with a flourishing summary, I wish to note down some of the more contentious points in a way that is designed to provoke discussion. In addition, I will suggest some practical steps that can be taken to investigate some of the issues, and to address them in science teaching. (References listed at the end may be helpful to you.)

Let us begin with the argument itself.

1. The argument started with an account of the growth of knowledge:
   a) In your teaching area or area of interest, how much has knowledge grown over the last five or ten years?

2. Next, I argued that most of what we mean by critical or scientific thinking is basically puzzle-solving and logic-wielding.
   a) Can you find examples of "thinking" in lessons, quizzes, or classroom tests and assignments which cannot be seen as puzzle-solving and logic-wielding?
   b) Try taping and transcribing a lesson, and then ask, "What sorts of thinking appear to be demanded by the teacher?"

3. I steadfastly avoided any reference to the psychology of thinking or "how people think," because this literature is connected very largely to the sorts of thinking manifested in the test items already seen, and for the following reason: The effort to build theories which explain human thinking is not entirely relevant to education, because theories that answer the question "How do you think?" simply cannot come close to answering the question "How <u>should</u> we think?" What do you think?

4. I demonstrated that the basis of scientific knowledge had to do with understanding that science constructed a world. This, I claimed, ought to be evident in the way we speak of concepts, theories and explanations as being formulated by humans.

   a) What are the dangers, if any, of failing to provide youngsters with an appropriate understanding of the context of scientific knowledge?
   b) What is an appropriate context?
   c) What do youngsters currently understand about the nature of scientific knowledge? (See below for ways to investigate this question.)

5. Last, I urged that science teaching make provision for youngsters to be intellectually independent so that they have the equipment to make judgements about scientific knowledge for themselves.

   a) Does teaching currently make provision for intellectual independence? Do textbooks? (See below for some suggestions for answering these questions.)
   b) If we don't stimulate intellectual independence, are we miseducating our youngsters? (This demands a consideration of what we mean by "education.")
   c) Can we, and should we, be intellectually independent? (This leads to the broader question of what it means to live as a responsible member of society, abiding by its conventions.)

What is the Present State of Affairs?

My argument has been illustrated with examples drawn from science lessons. No pretence is being made that these excerpts represent the contemporary state of science teaching; instead, the material draws attention to certain features of intellectual independence and the context of the language of science by pointing to dialogue and asking, "What can learners get from this?" Yet, one cannot read transcripts like these without wondering how much of science teaching resembles such excerpts and what youngsters currently understand about the nature of scientific knowledge. Here are two rather different approaches that you can take to getting a feel for the present state of affairs.

1. The first approach is to examine some teaching. You begin by identifying a science teacher who is willing to have you tape a lesson. (It could be one of your own lessons.) Tape the lesson, and then transcribe it. Next use the features of intellectual independence and your knowledge of the context of the lesson to analyze the transcription to see whether it provides for intellec-

tual independence or intellectual dependence. This work will take some time, and you may wish to repeat it for other lessons. If your interest in this approach to analyzing educational phenomena is sparked, try the same sort of technique on a few chapters of the science textbooks that are presently used in school science programs at all levels. I won't be so presumptuous as to predict what you'll find, but I'll hazard a guess that you'll be very intrigued.

2. The second approach asks, "Why don't we try to describe how youngsters in science courses understand terms like theory, model, scientific law, principle, and concept?" This is not as easy as it might sound, because if we simply ask youngsters to explain what is meant by "theory" (by giving them a questionnaire, say), then we may get a stilted definition of what they think we want them to know a theory to be. All of this will be given without the context of their understanding. So, the procedure must be clinical. One approach would be to work with a single youngster, posing the following sorts of questions with a tape recorder running:

   a) When we speak of Newton's laws of motion, what do you think is meant by "law"?
   b) What sort of thing is a theory in science? You can use an example to explain to me what you understand the term "theory" to mean.
   c) When we talk in science about "fundamental particles" (or any other conceptual entity the interviewer thinks may elicit interesting information) what do you think a scientist means? Does he or she mean that these particles are really there, or is there some other implication?

Questions like these will need to be followed by others in an effort to thoroughly grasp what the student understands. This is a lengthy process, and a single interview of say, 45 minutes may turn out to serve no other function than to show how the interviewing techniques could be improved. You might want to work with children of different ages to get an idea of a developing understanding. When all the tapes are collected, they must be carefully listened to, and if you think that the children's understanding is inadequate, it is the clearest indicator of a problem for science education to address.

What Changes Can be Made?

A great difficulty with what I'm advocating is the real chance that curriculum change will be thwarted simply because there is insufficient time to add anything on the nature of scientific knowledge to an already overburdened curriculum. I want to take two different approaches to this problem, the first being more abrupt than the second.

If what I have said about the fundamentals of scientific thinking is truly valuable, then it has to be incorporated within the school science curriculum. If this curriculum is already full, then some of the material must be discarded, to be replaced by units which introduce students to the nature of science. This could probably be achieved in the junior and intermediate levels without great loss. Certainly, such units must be available to all students, whether or not they plan to specialize in science, because leaving the matter until grade 12 or 13 is somewhat akin to closing stable doors after the horses have escaped. However, major changes like this are unlikely to take place, and an alternative ought to be offered for consideration.

There is no reason why great strides towards intellectual independence cannot be made through minor adjustments to our present teaching. We must speak of theories as inventions, we must remind learners that scientific constructions are models of reality and not more, and we must be sure that we offer evidence for our claims and deal with our students' contributions in a rational manner. In short, we must discard the motto "Don't do as I do, but do as I say" and make "Do as I do" a template for our teaching.

This sort of approach can be run through a year's programs, but it will reach learners only if they have a context for the language. So it is important during a course, particularly at the beginning, to set time aside (perhaps one or two periods) for teaching very clearly the nature of scientific theories. This can be achieved without loss of precious "content-time" by working an emphasis on the nature of science into the first unit of a course. (Sources for this type of approach are given below.) In this way, we can be confident that our teaching coincides with the basis of scientific thinking and so allows students to pick up and use this significant facility.

Below, I suggest a few questions that could be considered when beginning a new course or unit:

1. Is it possible to adapt the first few lessons in several units throughout a course, and especially at the beginning of a course, so that an emphasis on the nature of science is provided?

2. What sorts of teaching content and strategy would work well here?

3. (For those who do attempt to make a change as indicated in questions 1 and 2.) On the basis of talking with youngsters individually, do you detect a better understanding of the nature of scientific knowledge?

APPENDIX: AN ANNOTATED LIST OF SOURCES

Hugh Munby, "Analyzing Teaching for Intellectual Independence," in Seeing Curriculum in a New Light: Essays From Science Education, ed. Hugh Munby, Graham Orpwood and Thomas Russell, Ontario Institute for Studies in Education, Toronto, 1980. This paperback is aimed at those interested in a variety of educational phenomena. The chapter cited here contains a full treatment of intellectual independence, along with a substantial analysis of transcribed lessons.

Hugh Munby, "Some Implications of Language in Science Education," Science Education, vol. 60, no. 1, 1976. My paper takes Toulmin's account of the nature of scientific knowledge and applies it to some extracts from science textbooks. The failure of the texts to indicate the special context of language in science and the confusing implications for a reader is revealed.

Douglas Roberts, The Mole as an Explanatory Concept: How Do You Know a Mole if You See One?, Department of Curriculum, Ontario Institute for Studies in Education, Toronto, 1972. This booklet is a sample teaching unit expressly designed to give emphasis to the nature of science when teaching the mole concept. It contains text material and corresponding discussion material.

Douglas Roberts and Graham Orpwood, Properties of Matter: A Teacher's Guide to Alternative Versions, Ontario Institute for Studies in Education, Toronto, 1979. The real strength of this publication, from the Intermediate Science Curriculum Project, is that it shows how a lesson can be taught in three different ways, each to give a particular and different emphasis. The first of these is the "Nature-of-Science Emphasis."

Stephen Toulmin, The Philosophy of Science: An Introduction, Harper and Row, New York, 1960. Available in paperback, this book contains the most readable account of the nature of scientific knowledge that I know. The approach taken is to examine geometric optics, and the language is not technical. The book would make excellent required reading for science students in grades 12 and 13, and for first-year university students.