THE PUPIL AS SCIENTIST?

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PREFACE

Discovery methods in science teaching put pupils in the role of investigator, giving them opportunities to perform experiments and test ideas for themselves. What actually happens in classrooms when this approach is used? Although, of course, pupils' ideas are less sophisticated than those of practising scientists, some interesting parallels can be drawn. The work of Thomas Kuhn indicates that, once a scientific theory or paradigm becomes established, scientists as a community are slow to change their thinking. Pupils, like scientists, view the world through the spectacles of their own preconceptions, and many have difficulty in making the journey from their own intuitions to the ideas presented in science lessons.

This book is an attempt to describe events along the path of the pupil as scientist. Its intention is to be descriptive rather than prescriptive. It contains many examples of pupils' dialogue and written work. Most of the examples were collected while making a study over a 4-month period of a science class at the University of Illinois Curriculum Laboratory. As the excerpts indicate, the teacher encouraged the class to investigate phenomena and to make their own inferences. In order to indicate in some detail the development in pupils' thinking, a small group of pupils was selected for detailed study.

Further examples from other science lessons have also been used. Most of these are examples of pupils' work from classes I have observed or taught myself.

The first chapter of the book makes the case that pupils do come to science lessons with already formulated ideas, or alternative frameworks, and that these may be at variance

with the theories the teacher may wish to develop. The examples in this chapter also illustrate the fallacy of the simple inductive method in science teaching.

In later chapters I give further examples of common alternative frameworks, and how these affect pupils' observations and the sense they make of them.

Currently, research on children's thinking in science is focused on the development of children's logical abilities. A further chapter indicates, with examples, the limitations of this position in understanding children's thinking, and suggests that more attention needs to be paid to the development of specific ideas and concepts as opposed to generalized thinking skills.

Inevitably, the book raises questions about classroom practice. Here I recognize the danger of being prescriptive and recommending simplistic solutions to complex problems. However, implications for secondary science courses are raised and general suggestions for classroom practice are made in the last chapter.

A paper outlining a method for representing children's frameworks in science, with particular reference to ideas in dynamics, is included in the Appendix.

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THE FALLACY OF INDUCTION IN SCIENCE TEACHING

Science is not just a collection of laws, a catalogue of facts, it is a creation of the human mind with its freely invented ideas and concepts. Physical theories try to form a picture of reality and to establish its connections with the wide world of sense impressions.

A. Einstein and L. Infield,
The Evolution of Physics, (1938).

In our everyday life as adults we operate with a very complex set of beliefs and expectations about events. An egg rolls across the counter top in the kitchen and we know where to make a grasp for it before it falls over the edge and smashes to the floor. The fact that so many of us can drive around on our roads without more accidents occurring is possible because of the sets of expectations we have developed enabling us to predict the speed and movement of other vehicles on the road and the probable behaviour of pedestrians. Such sets of expectations mean we can live our daily lives without being constantly in a state of disorientation and shock. Similarly, children construct sets of expectations or beliefs about a range of natural phenomena in their efforts to make sense of everyday experiences.

A 10-year-old switched off the radio, noticed with surprise that it took over a second for the sound to fade away and commented: 'What a long length of electric wire there must be in that radio when you think how fast electricity travels.' Without any formal instruction, this child had already developed certain ideas about electricity, notably that it travels down wires, and that it travels very fast.

From the very earliest days in its life, a child develops beliefs about the things that happen in its surroundings. The baby lets go of a rattle and it falls to the ground; it does it again and the pattern repeats itself. It pushes a ball and it goes on rolling across the floor. In this way, sets of expectations are established which enable the child to begin to make predictions. Initially, these are isolated and independent of one another. However, as the child grows older, all its experiences of pushing, pulling, lifting, throwing, feeling and seeing things stimulate the development of more generalized sets of expectations and the ability to make predictions about a progressively wider range of experiences. By the time the child receives formal teaching in science it has already constructed a set of beliefs about a range of natural phenomena. In some cases, these beliefs or intuitions are strongly held and may differ from the accepted theories which science teaching aims to communicate.

One of the features of the science teaching schemes which have been developed over the last 20 or 30 years is a rejection of science as a catalogue of facts. Instead, teaching schemes have been produced which present science as a coherent system of ideas. Focus is on the integrating concepts or big ideas such as atomic theory in chemistry or kinetic theory in physics. Apart from doing justice to the nature of scientific theory itself, one of the important arguments for such an approach suggested by Bruner[1] is that it helps pupils to apply ideas to new situations if the connections between those ideas are made explicit in teaching. Put in psychologists' jargon, it encourages 'transfer'.

One of the problems with this argument is that the connections that are apparent to a scientist may be far from obvious to a pupil. It is, after all, the coherence as perceived by the pupil that matters in learning. In developing science teaching material little attention has yet been paid to the ideas which children themselves bring to the learning task, yet these may have a significant influence on what children can and do learn from their science lessons. Over a decade ago, the psychologist David Ausubel commented on the importance of considering what he called children's preconceptions, suggesting that they are 'amazingly tenacious and resistant to extinction . . .' and that '. . . unlearning of preconceptions might well prove to be the most determinative

single factor in the acquisition and retention of subject matter knowledge'.[2]

This perspective on learning suggests that it is as important in teaching and curriculum development to consider and understand children's own ideas as it is to give a clear presentation of the conventional scientific theories. After all, if a visitor phones you up explaining he has got lost on the way to your home, your first reaction would probably be to ask 'Where are you now?' You cannot start to give sensible directions without knowing where your visitor is starting from. Similarly, in teaching science it is important in designing teaching programmes to take into account both children's own ideas and those of the scientific community.

By the time children are taught science in school, their expectations or beliefs about natural phenomena may be well developed. In some cases these intuitions are in keeping with the ideas pupils will meet in their science lessons. They may be poorly articulated but they provide a base on which formal learning can build. However, in other cases the accepted theory may be counter-intuitive with pupils' own beliefs and expectations differing in significant ways from those to be taught. Such beliefs I shall refer to as 'alternative frameworks'. This book explores aspects of the relationship between pupils' alternative frameworks and science teaching: how they affect pupils' interpretations of the practical experiences given in science lessons and influence the observations made.

Another characteristic of the science curriculum development of the last few decades has been an emphasis on the heuristic method. This was prompted by the admirable concern to allow children to experience something of the excitement of science—'to be a scientist for a day'.[3] We are now recognizing the pitfalls of putting this approach into practice in classrooms and laboratories. Secondary school pupils are quick to recognize the rules of the game when they ask 'Is this what was supposed to happen?' or 'Have I got the right answer?'[4,5] The intellectual dishonesty of the approach derives from expecting two outcomes from pupils' laboratory activities which are possibly incompatible. On the one hand pupils are expected to explore a phenomenon for themselves, collect data and make inferences based on it; on the other hand this process is intended to lead to the currently accepted scientific law or principle.

Some insight into this problem can be gained by considering different views of the nature of science. The most simplistic view of the scientific enterprise is, perhaps, the empiricist's view, which holds that all knowledge is based on observation. Scientific laws are reached by a process of induction from the 'facts' of sense data. Taking this view of science, observations are objective and facts immutable. Also, such a position asserts that science will produce a steady growth in knowledge: like some international game of 'pass the parcel', the truth about the natural world will be unwrapped and gradually more will be revealed.

This inductivist position was criticized when it was first suggested by Bacon nearly 400 years ago, yet it has reasserted itself early in this century in the heuristic movement and later in some of the more naive interpretations of the discovery method adopted by the Nuffield science schemes.

For a long time philosophers of science and scientists themselves have recognized the limitations of the inductivist position and have acknowledged the important role that imagination plays in the construction of scientific theories. In this alternative constructivist or hypothetico-deductive view, theories are not related by induction to sense data, but are constructions of the human mind whose link with the world of experience comes through the processes by which they are tested and evaluated.

Currently there are different views about the criteria for acceptance or rejection of scientific theories.[6] The philosopher Popper asserts that, in addition to the individual's mental world, there exists a world of objective knowledge[7] which has properties which can be assessed by logical principles without regard to the person or group of people who generated that knowledge. Others subscribe to a more subjective position. Polanyi,[8] for example, in his writings, indicates the importance of the commitment of an individual to a theory, a commitment which may be influenced by factors other than logic, with aesthetic criteria playing an important part. Science as a cooperative exercise as opposed to an individual venture is emphasized in the writings of Kuhn[9] and Lakatos[10]. Viewed from a sociological perspective, such writers suggest that the criterion for acceptance of a scientific theory is that it is scrutinized and approved by the community of scientists.

Although there are these differences of view on the objectivity of scientific knowledge and the criteria for assessing theories, there is general agreement on two matters of importance to school science. The first is the recognition of pluralism in scientific theories. Following from this is acceptance of the revolutionary nature of science; that progress in scientific knowledge comes about through major changes in scientists' theories (or paradigms). This gives science educators the task of 'teaching consensus without turning it into an orthodoxy.'[11] The second point of agreement is about the nature of observations: these are no longer seen as objective but influenced by the theoretical perspective of the observer.[12] As Popper said, '. . . we are prisoners caught in the framework of our theories'.[13] This, too, has implications for school science, for children, too, can be imprisoned in this way by their preconceptions, observing the world through their own particular 'conceptual spectacles'.

The implications of paying more than lip service to this constructivist view of science are explored in some detail throughout the book. Here I will illustrate some main points with a couple of classroom examples. The first example illustrates the hypothetico-deductive nature of science enquiries. It shows an investigation taking place, not from observation to generalization, but being initiated by a hypothesis which in this case derives from a pupil's alternative framework.

Two 11-year-old boys, Tim and Ricky, are doing simple experiments on the extension of springs when loaded. They have made their own spring by winding wire round a length of dowel. One end of the spring is supported in a clamp and a polystyrene cup is hanging from the other end (Figure 1, p.6). Following instructions, they investigate the extension of the spring as they add ball bearings to the polystyrene cup. Ricky is adding the ball bearings one at a time and measuring the new length of the spring after each addition. Tim is watching him, then interrupts:

> How far is that off the ground? Pull it up and see
> if the spring does not move any.

He unclamps the spring, raises it higher up the stand, and again measures its length. Apparently satisfied that the length is the same, he continues with the experiment. Later, when he was asked the reason for doing this, he explained that he

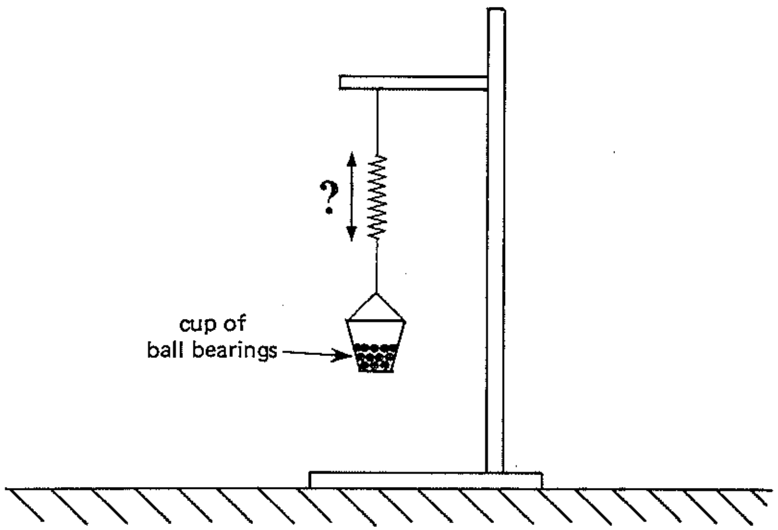

Figure 1

thought the weight of the cup of ball bearings would increase if it were raised. To explain his reasoning, he picked up two marbles and held one up higher than the other:

> This is farther up and gravity is pulling it down harder—I mean the gravity is still the same but it turns out it is pulling harder the farther away. The higher it gets the more effect gravity will have on it because, like if you just stood over there and someone dropped a pebble on him, it would just sting him, it wouldn't hurt him. But like if I dropped it from an aeroplane it would be accelerating faster and faster and when it hit someone on the head it would kill him.

It appears that Tim's idea of weight encompasses the notion of potential energy and leads him to predict a greater extension of the spring when it is further from the ground. He uses the same framework when considering the force required to hold a trolley at different positions on an inclined board,

predicting that it will be harder to hold when it is higher up than when it is lower down the slope.

Not only does this example indicate how pupils' alternative frameworks can intrude into their activities in science lessons, it illustrates how, in some cases, alternative frameworks are more than an idiosyncratic response to a particular task, they may be general notions applied to a range of situations.

There is evidence from a number of investigations that pupils have common alternative frameworks in a range of areas including physical phenomena such as the propagation of light, simple electrical circuits, ideas about force and motion and chemical change, also biological ideas concerned with growth and adaptation.

It follows from a constructivist philosophy of science that theory is not related in a deductive, and hence unique, way to observations; there can be multiple explanations of events which each account for the data. In the example of Tim's idea of weight we see how he had developed an idea based on common experiences with falling objects, yet he had explained them to himself in a way that differed from the accepted physicist's view. The possibility of multiple interpretations of an event is also illustrated in the following example of work done in a science class of 12-year-old pupils. A pair of girls were doing an experiment in which an immersion heater was placed in blocks of different metals, each of the same weight (Figure 2, p.8). The pupils had been instructed on a worksheet to draw a temperature-time graph for each block as it was heated. The purpose of the experiment being to illustrate variation in specific heat capacities of different metals. The girls had chosen blocks of iron and aluminium, and towards the end of the lesson they were instructed to look at their graphs, compare them and suggest explanations for any differences. Here are their comments:

P1: We've got to do a graph for the aluminium.
P2: Good. Aluminium isn't so—um—it—
P1: Don't forget it has to go through, doesn't it? Through the thickness to reach there—the thermometer.
P2: That was only thin to get to that.
P1: Come on, we've got to put it away now.

The teacher enters the discussion.

T: What has your experiment shown you?
P2: That different—um—that different materials and that see how heat could travel through them.
T: What did you find out?
P1: Well—er—that heat went through the—the iron more easier than it did through the—er—
P2: Aluminium.

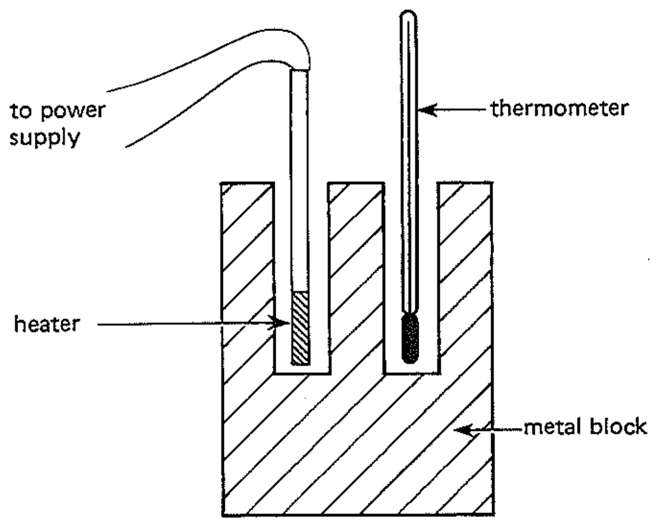

Figure 2

Here pupils had performed the experiment and had collected their data, yet it appears from their comments that they interpreted the difference between the graphs for the two metal blocks not in terms of the amount of heat required to raise the temperature of each by a certain amount, but in terms of the comparative conductivity of metals.

The more simplistic interpretations of the discovery approach in science suggest that we only need to give pupils the opportunity to explore events and phenomena at first hand and they will be able to induce the generalizations and principles themselves. The position suggested here is that

children do make generalizations from their firsthand experiences, but these may not be the ones the teacher has in mind. Explanations do not spring clearly or uniquely from data.

Through the eyes of those initiated in the currently accepted theories of science, common school demonstrations, such as trolleys and ticker tapes, experiments with batteries and bulbs, or work with ray boxes, mirrors and prisms, appear to offer self-sufficient support for the underlying principles they are designed to demonstrate, whether it is Newton's Laws of Motion or the Laws of Reflection of Light. If children fail to abstract and understand these principles from their experiments, it may be seen as the children's error either for not observing accurately or not thinking logically about the pattern in the results.

The constructivist view of science, on the other hand, indicates the fallacy here. If we wish children to develop an understanding of the conventional concepts and principles of science, more is required than simply providing practical experiences. The theoretical models and scientific conventions will not be 'discovered' by children through their practical work. They need to be presented. Guidance is then needed to help children assimilate their practical experiences into what is possibly a new way of thinking about them.

The slogan 'I do and I understand' is commonly used in support of practical work in science teaching. We have classrooms where activity plays a central part. Pupils can spend a major portion of their time pushing trolleys up runways, gathering, cutting and sticking tangling metres of ticker tape; marbles are rattled around in trays simulating solids, liquids and gases, batteries and bulbs are clicked in and out of specially designed circuit boards. To what end? In many classrooms, I suspect, 'I do and I am even more confused'.

This process of 'making sense' takes on even greater significance when considering children's alternative frameworks. Not only do children have to comprehend the new model or principle being presented to them, but they have to make the intellectual leap of possibly abandoning an alternative framework which until that time had worked well for them.

To use the language of philosophy of science, children sometimes need to undergo paradigm shifts in their thinking. Max Planck suggested that new theories do not convert

people, it is just that old men die. If scientists have this difficulty in reformulating their conceptions of the world, is it a wonder that children sometimes have a struggle to do so?

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2

LEARNING TO OBSERVE

Enter a laboratory; approach the table crowded with an assortment of apparatus, an electric cell, silk-covered copper wire, small cups of mercury, spools, a mirror mounted on an iron bar; the experimenter is inserting into small openings the metal ends of ebony-headed pins; the iron oscillates and the mirror attached to it throws a luminous band upon a celluloid scale. The forward—backward motion of this spot enables the physicist to observe the minute oscillations of the iron bar. But ask him what he is doing. Will he answer 'I am studying the oscillations of an iron bar which carries a mirror'? No, he will say that he is measuring the electric resistance of the spools. If you are astonished, if you ask him what the words mean, what relation they have with the phenomena he has been observing and which you have noted at the same time as he, he will answer that your question requires a long explanation and that you should take a course in electricity.

P. Duhem, *The Aim and Structure of Physical Theory*, Philip P. Weiner Trans. (1962).

This passages illustrates how a naive observer of an electrical experiment sees various aspects of the apparatus: ebony-headed pins, cups of mercury, a mirror, a celluloid scale. Yet without the conceptual framework of the physicist he cannot discriminate between the relevant and the irrelevant aspects. Nor does he understand how they relate together.

One of the reasons commonly given for teaching science in schools is that it trains pupils to be observant, to be objective and precise in their reporting and recording of events. But as this quotation from Duhem illustrates, different people looking at the same thing may be perceiving it rather differently. 'Looking at' is not a passive recording of an image like a photograph being produced by a camera, but it is

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which is in conflict with expectation it is the latter which takes priority.

It might be argued, therefore, that it is people's intuitions in science which need educating rather than their capacity for logical thought.

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8

FROM THEORY TO PRACTICE

Gott

Whenever we plan and teach a science course we make decisions, whether explicitly or implicitly, about the aims of the course. For example, is it to be a course that is appropriate for all secondary school pupils or is it to be a preparation for pupils specializing in science? Is the course to be responsive to the interests and ideas of young people or is it primarily to reflect the structure of the discipline? What image of science does it promote—is it science as a body of knowledge or is there a place for inquiry and speculation on the part of pupils?

The 1981 policy statement of the Association for Science Education[1] lists six aims for education through science which might be summarized as follows:

(1) understanding scientific concepts,
(2) the development of cognitive and psycho-motor skills,
(3) the ability to undertake inquiries,
(4) understanding the nature of the scientific enterprise,
(5) understanding the relationship between science and society,
(6) the development of a sense of personal worth.

The document indicates that all young people at some point in their schooling should have experiences which lead to the achievement of all these six aims, although it recognizes that the needs of different young people may demand different emphases at various times in their schooling.

Developing and teaching courses which reflect this

balance is a very real challenge, not least because of some possible inherent conflicts between the aims themselves. This book has explored some of the issues involved in producing a satisfactory synthesis between just two of the aims: the acquisition of knowledge and the use of pupils' own inquiries in the pursuit of further knowledge. The tension between these two components has existed for as long as science has had a place in the school curriculum.

Over the last 100 years documents on the role of science in general education have reflected this tension. In a report, *Natural Science in Education*, published in 1918,[2] the authors make an eloquent claim for science in the school curriculum in terms of the general faculties it develops:

> It can arouse and satisfy the element of wonder in our natures. As an intellectual exercise it disciplines our powers of mind. Its utility and applicability are obvious. It quickens and cultivates directly the faculty of observation. It teaches the learner to reason from facts which come under his own notice. By it, the power of rapid and accurate generalization is strengthened, without it, there is a real danger of the mental habit of method and arrangement never being acquired.

In 1936 the Science Masters' Association published a report, *The Teaching of General Science*,[3] in which it states three main contributions that science makes to general education:

(1) utilitarian or vocational: it helps the pupils in their everyday life, or may be necessary in their future occupations;
(2) disciplinarian: it teaches them to think; it sharpens their minds;
(3) cultural: its inclusion is desirable because it forms an essential part of our social heritage.

Again, the claim is made that science makes an important contribution to the development of pupils' general faculties, although the report later adds a cautionary note:

> ... we would point out, however, that *experimental* evidence has shown quite definitely that the possibilities of transfer of training are much smaller than had formerly been supposed.

The 'process' aims of science education have also been of concern to American curriculum developers since the 1950s.[4] The curriculum development projects in secondary science which have taken place since the 1950s in Britain and America have attempted to foster the skills of scientific inquiry and to promote an understanding of scientific principles and their application to everyday life.

As I indicated earlier, the traditional synthesis between these two aims has tended to promote an inductivist view of science based on the premise that all scientific knowledge derives from sensory experiences. This perspective has been reinforced over the years by views about child-centred education, as articulated by such people as Froebel, Dewey and Piaget.

Incidentally, it would be incorrect to suggest that psychologists and philosophers of science have been influential in shaping the science in our schools. Rather the community of science educators has invoked such theoretical 'support' as is necessary to give credibility to 'common sense' views about the nature of science and of children's learning. The problems that exist both with the inductivist view of the nature of science and with the 'accretion' view of children's learning have been outlined in earlier chapters. It appears that it is necessary to piece together a new synthesis between content and process in science education which brings together both a different philosophy of science and a new perspective on learning. This involves the recognition that the science that children learn beyond primary school is more than natural history; it goes beyond the exploration and classification of aspects of the environment. Pupils are being introduced to theoretical ideas and conventions of the scientific community, ideas which derive from the imagination and which may in time be superseded.

If this constructivist view of the nature of science is to be taken seriously then it has certain implications for secondary school science courses. This chapter gives a personal view of a number of these implications.

A developmental approach to science teaching and learning

Throughout the book, evidence has been presented which indicates that children use a range of intuitive ideas to make sense of their experiences. Some of these ideas, or alternative frameworks, are characteristic of the thinking of many children, and may persist despite instruction. Perhaps it is not surprising to note the similarity between some of the ideas of children and theories that have been important in the history of science itself (for example the caloric theory of heat or Aristotelean views of motion). Daily experiences of phenomena make some interpretations or models more obvious than others. However, it is very easy to view the notions put forward by pupils as naive and simplistic, and to pass them by, perhaps with disinterest. It is perhaps worth bearing in mind that some of these notions were given serious consideration in the scientific community in the past. By referring to the ideas and investigations of past scientists, some of the powerful ideas of young people can be explored in a way that treats them with respect. It has been suggested that, instead of ignoring the alternative frameworks that children have developed, science teaching programmes could benefit by taking greater account of them. By making their theories more explicit in the formal learning situation children are able to explore their implications and make comparisons between one 'framework' or 'theory' and another. They can also be given experiences which serve to develop their ideas or, if necessary, to challenge them. Various science teaching materials have attempted to do this. One of the most well-developed examples is the treatment given to dynamics by the Harvard Project Physics materials,[5] where the Aristotelean view is explored at some length.

Educators have always recognized the need to 'start where the child is'. Ausubel emphasizes this in the distinction he makes between 'meaningful' and 'rote' learning. In practice this is usually interpreted in terms of relating science teaching to experiences which are familiar to children in their daily lives.

However, perhaps in addition, teaching needs to relate to what is familiar to children, not just at the level of the world of events and experiences but also in their world of ideas. If children are encouraged to make their theories more explicit, these can be open for inspection and testing in the classroom. Children's own ideas in fact can provide the necessary raw material to exemplify the plural nature of scientific theory, and act as a starting point for pupils to design critical tests to distinguish between different interpretations.

Underlying this recognition that children's ideas as well as their experiences need to be taken into account in planning courses is a view of the learning process as taking place by conceptual change. The task for educators is to give pupils the experiences which encourage such change to take place. In preparing secondary science courses little attention has as yet been paid to what is known about the development of pupils' thinking. Such projects as Science 5/13 and the Australian Science Education Project have based their sequencing of materials on a Piagetian stage model. In this kind of scheme, ideas which involve the structures of formal operational thought such as arguing hypothetico-deductively, controlling variables or using proportional reasoning are not introduced until the adolescent years.

Shayer and Adey[6] report their analysis of the cognitive demand of a range of secondary science courses in terms of Piagetian levels, and the results of a survey of the levels of thinking of British schoolchildren. The findings indicate a mismatch exists between the logical demands of the science courses analysed and the level of thinking of most secondary school pupils.

Such an analysis may give general guidance on matching the demands of a course to the logical capabilities of the pupils taking it. It can be helpful in giving a general indication of the way ideas can be sequenced for teaching and at what age they might be introduced. However, there is more involved in taking account of children's thinking than simply paying attention to its logical component. In a previous chapter doubt was expressed about the Piagetian matching model and it was indicated that the content as well as the logical structure of a task affects pupils' performance.

In some science topics investigations of pupils' ideas indicate that these develop with age through a clear sequence, and a knowledge of this can be helpful both in deciding at what age to teach a topic and how to organize appropriate experiences for pupils: experiences which will aid their con-

ceptual understanding of that topic. Some of the interesting approaches being tried which are based on this view of learning as conceptual change have been reviewed in earlier chapters. Techniques which are being incorporated into these approaches include providing opportunities for pupils to make their own ideas explicit, encouraging the generation and testing by pupils of alternative interpretations of phenomena, and giving pupils experiences which challenge their current ideas.

The question of structure in the science curriculum

Such a view of learning through conceptual change has implications for the general organization of the science curriculum. In his influential book, *The Process of Education*, Jerome Bruner drew attention to the importance of the structure of the subject to be taught:

> . . . the curriculum of a subject should be determined by the most fundamental understanding that can be achieved of the underlying principles that give structure to that subject. Teaching specific topics or skills without making clear their context in the broader fundamental structure of a field of knowledge is uneconomical in several deep senses.[7]

Much of the science curriculum development that has taken place over the last two decades on both sides of the Atlantic has indicated this concern for structure. The content of science courses has been updated and their structure changed to reflect recent developments in the conceptual structure of the discipline. Paradoxically, this has been coupled with a shift in pedagogy towards a greater amount of practical work; practical work which in most cases is introduced to be illustrative or provide confirmatory evidence for the presented theories. We tend to think that this 'practical' approach makes the subject more 'relevant' and easier for pupils to understand. Yet there is a sense in which the approach is making even more intellectual demands on pupils in that it requires pupils to relate experiences obtained in the laboratory to the theoretical models being presented. The pupils themselves, with or without guidance, need to make

the connection between the phenomena and the theoretical constructs: for example, to link the movement of levels of liquids in tubes to the increased motion of invisible particles which 'compose' the liquid, to relate the change in colour of a solution in a test tube to the concentration of hydrogen ions present. It is important to recognize that in science lessons pupils are involved in learning at two levels at once: they are exposed both to new phenomena and also to their accepted theoretical interpretation. Simply because teaching based on conceptual schemes is problematic does not mean it should not be attempted. However, the demands it makes on pupils need to be recognized. If pupils are unable to link the experiences given in the laboratory to the conceptual themes in the course, then the coherence that is apparent to the curriculum writer or teacher may not be obvious to the pupils, who may remember it simply as a series of disjointed experiences. Incidentally, the current debate over teaching science as separate disciplines or as an integrated course may be an irrelevant issue to many pupils who remember their experiences as a sequence of lessons, whatever the subject is called on the timetable. The key question is 'what is integrated by the learner?'

Even though they have difficulty relating the phenomena to the presented theory, some pupils are prepared to suspend judgement, to learn the rules or laws even though they cannot relate them to their experiences. They are able to maintain interest in the belief that at a later date what they are learning will make sense. On the other hand, many secondary school pupils, perhaps the majority, expect more immediate intellectual satisfaction. They are not prepared to wait weeks or even years before theoretical ideas presented in school can be related to their own experiences. Many of these pupils will never continue with their formal science education after leaving school. Such pupils need to be able to 'make sense' of the scientific ideas presented to them in a more immediate way.

School science may be remembered, but recalled as isolated experiences; some activity with glass blocks and pins may be remembered in much the same way as a snatch of a Wordsworth poem or an unrelated fact in history. It has not become part of the young adult's way of understanding the natural world. Unless the theory or formalism presented to

pupils is learned in a meaningful way, it is soon forgotten as useful knowledge and not drawn on in the future: pupils revert to their intuitions or earlier frameworks. The problems that this can cause have been illustrated in earlier chapters. Designing a curriculum around major conceptual schemes may mean that most pupils finish their formal education in science neither understanding the theory they have been introduced to nor seeing the illustrative phenomena as particularly relevant or interesting.

If the orientation of science in general education is to help pupils develop a theoretical understanding which enables them to interpret and make sense of everyday experiences, to make pupils more 'at home' in the natural and man-made world they inhabit, then this may mean reassessing the science curriculum at two levels. It means selecting illustrative phenomena not simply because of the support they give to a theoretical idea, but because they are of practical use and everyday interest in their own right. It also means bringing the theoretical ideas within the compass of pupils' understanding.

In many areas of science, phenomena can be interpreted at a range of levels of sophistication, all of which are in some sense useful. For example, in the early years of secondary school, we expect pupils to understand current electricity in terms analogous to fluid flow in pipes. This model is quite effective in enabling us to predict or explain a range of everyday phenomena involving electrical circuitry; in this sense the model is 'right', it is adequate for its purpose. However, older pupils are introduced to a more sophisticated model in which electric current in wires is construed as a drift of charged particles through a lattice structure. This model is only 'better' than the previous one in that it accounts for a greater range of phenomena. A similar shift in the level of theoretical sophistication is encountered in several other topics, for example, in chemical bonding, the wave properties of light, inheritance and the molecular—kinetic theory of heat.

For pupils who have difficulty in understanding the theoretical ideas in science perhaps it is necessary to reconsider the level of theory presented. For example, are we justified in placing so much emphasis in basic science courses on the kinetic—molecular model when pupils have such difficulty in understanding it well enough to be confident in

using it? Would it be more appropriate to accept a caloric notion of heat from younger secondary school pupils? After all, members of the building trade, for example, operate effectively in their calculations of heat conductivity of materials in terms of 'quantities of heat' and 'rates of flow'. From the pupils' point of view it is perhaps preferable to have a workable model to interpret phenomena, even if it has to be changed at a later date, rather than to be exposed to more sophisticated ideas which only confuse.

There are those who will oppose such a suggestion, arguing that we should never teach anything that has to be 'unlearned' later. In response, I would argue that such a view simply does not reflect much of our experience, either in formal learning contexts or in everyday situations. We are continually being placed in situations where we have to revise, develop or discard ideas in the light of new evidence. The challenge this faces us with in science education is to present theories to pupils so that they can be understood and yet not be taken as immutable truths. There is an important distinction to be made here between understanding and belief: it is possible and important to be able to *understand* alternative interpretations, those suggested by other pupils or other scientists, without necessarily *believing* any of them.

The 'experimental method' and science teaching

In appraising the role of practical work in secondary school science, a number of types of activity can be distinguished. There are those whose purpose is to extend pupils' knowledge of phenomena, others are used to illustrate and confirm 'accepted' principles. In addition, there is a case for including opportunities for pupils to undertake their own investigations, not in order to establish an important principle, but to gain some experience in planning an experiment using their own initiative. The focus of such activities is not the result obtained, but the steps along the way: the design of experiment, the choice and use of the apparatus, the careful recording and interpretation of the results. In order that children can undertake such investigations in as honest and thorough way as possible, time may have to be set aside from what is often the main orientation of the teaching programme.

These experimental exercises offer an opportunity to encourage individual initiative and imagination. They may be important in giving pupils experience of the rational—empirical approach to problem-solving. However, the skills they encourage, skills of careful observation, measurement and logical argument, are as relevant to the garage mechanic, electrician or dressmaker as they are to the scientist. The case for including exercises of this kind in science lessons is not to exemplify the way that science itself proceeds, but to encourage general rational thought, and to give pupils a sense of confidence in their own capabilities.

To illustrate the way science itself proceeds, the focus needs to be on competing conceptual systems. In a paper, 'Towards an integration of content and method in the science curriculum', Noretta Koertge states the following conclusion:

> To understand the growth of science and to get a balanced picture of both its fallibility and its claims to soundness, one must use a pluralistic approach and study at least two competing systems in detail.[8]

In reaching that conclusion, it is argued that science proceeds not by an inductivist approach of making generalizations about data, but that progress is made when an accepted theory competes with a new theory for the interpretation of data. Such a pursuit is very different from what has been characterized as the 'scientific method'.

Koertge proposes that case studies of competing theories from the history of science would be appropriate material for teaching the methodology of science. However, one need not search the literature on the history of science for examples of competing systems: pluralism in conceptual systems already exists among pupils in science classrooms.

Alternative frameworks suggested by pupils offer teachers readily available opportunities to illustrate characteristics of the scientific pursuit through the appraisal of competing interpretations or conceptions of events. Nor are new science teaching schemes necessary: as Baddeley[9] outlines, there are many opportunities within the current Nuffield science schemes to exemplify and test out competing theories which derive either from children's ideas or from the history of science.

A question of time

Science is not just natural history, and education in science involves more than simply extending the range of children's sense experiences (though it may also do this). It is about introducing children to the conventional scientific interpretations of events and helping them reorganize their ideas accordingly. Children need more than practical experiences for this reorganization in their thinking to take place. And yet, particularly in lower secondary school, it is the practical work, especially group practical work, which often occupies the greatest proportion of teaching time. Laboratory work is an important feature of science teaching, yet we may not be making the most of this important resource. In their survey of secondary schools,[10] the HMI report that

> (Science teachers) believed that pupils should have first-hand practical experience in laboratories in order to acquire skills in handling apparatus, to measure constants and to illustrate concepts and principles. Unfortunately, practical work often did not go further than this and few opportunities were provided for pupils to conduct challenging experimental invesigations.

They suggest that an important reason for this is the constraint imposed by examination syllabuses.

Not only do pupils need time to undertake practical activities, but more time is needed to make the most of those that are undertaken. Where activities are intended to illustrate some concept or principle, then time is required for pupils to consider their results and generalize the findings to new situations.

In a study on group work in science, Sands[11] reports that a major omission in lessons was the necessary 'follow-up' relating to the group work. Many such practical lessons end abruptly when the prescribed task is complete and little, if any, time is given to the interpretation of the results obtained, although this is just as important as the activity itself. Pupils need time to think around and consolidate the new ideas presented to them. After all, they may have developed their own ideas as a result of many years of experience. It is unlikely that they will easily adopt new ways of thinking as a result of one or two science lessons. As was suggested in

an earlier chapter, opportunities to apply new concepts or ideas in a range of situations are important in consolidating pupils' understanding and helping to build a bridge between the presented theory and experience. Here there may be teaching techniques which can be borrowed from other school subjects. Just as science teachers have developed the necessary skills to organize group practical exercises, perhaps the time has come to consider the development of strategies to help children make more sense of those practical experiences. What is being suggested is not a return to a more didactic teaching, but an extension of the range of types of activities undertaken in science classes.

The suggestions made so far have one requirement in common, and that is *time*. It takes time to allow for speculative discussion in class, even more time is required if pupils are to follow up competing ideas or to undertake their own investigations. If the necessary time is to be allowed, then it appears inevitable that a careful appraisal of the content coverage of syllabuses is necessary. Of course, some hard decisions may have to be made as to which topics to include and which to leave out. But perhaps curtailing the syllabus is not too great a price to pay if as a result pupils gain greater confidence in their understanding of the ideas covered, and in addition have some time which can be specifically devoted to inquiries of their own, however simple.

The ideas suggested in this chapter indicate ways in which teachers can help pupils not simply to extend their sensory experiences through science lessons, but to understand the conventional theories and formalisms of the scientific community and to relate these to their experiences in a meaningful way. They suggest a role for teachers as mediators between the pupils' experiences and understandings and that of the scientific community.

The writers of the Bullock Report remind us of what this may involve in the following passage:

> What the teacher has in mind may be the desirable destination of a thinking process, but a learner needs to trace the steps from the familiar to the new, from the fact or idea he possesses to that which he is to acquire. In other words, the learner has to make a journey in thought for himself.[12]

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