CHAPTER 14 The constructivist paradigm and some implications for science content and pedagogy

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Through a comparison of the widely-held traditional view of science with the constructivist view of science, we argue that the constructivist view of the content of science has important implications for classroom teaching and learning. This alternative view of science concepts as human constructs, scrutinised by application of the rules of the game of science, raises many challenges for teachers. Reconceptualisation of teachers' views of the nature of science and of learning in science is important for a constructivist pedagogy. We argue here that open discussion of the 'rules of the game' of science would contribute to better learning in the classroom, since learners would be better equipped to change their existing concepts by knowing more about the nature of science itself.

The traditional image of science

Many teachers hold the view that:

- science *knowledge* is unproblematic
- science provides *right answers*
- *truths* in science are *discovered* by observing and experimenting
- choices between correct and incorrect interpretations of the world are based on *commonsense* responses to *objective data.*

This traditional image of science has been explored in a large number of commentaries; see, for example, Chalmers (1976), Nadeau and Desautels (1984).

Teaching based on this traditional view of science attempts to transmit to learners concepts which are *precise* and *unambiguous,* using language capable of *transferring* ideas from expert to novice (teacher to student) with *precision.* Textbooks are sources of facts and theories about the concrete world,

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exemplified by the following extract from a textbook about teaching science in the primary school, Jacobson and Bergman (1980):

> 'Electrical energy can be converted into other forms of energy. As we have seen electrical energy can be transferred considerable distances along conductors. Another great advantage of electrical energy is that it can be readily converted into other forms of energy.' (p. 44)

The expectation is that teachers read this material, come to the same understandings as the authors, and then transmit the concepts to their students. The students who learn these statements come to know about electrical energy. There are a number of problems here.

- Study of the ideas students bring to lessons about energy reveals a variety of person-centred views related to 'needing energy to do things', 'needing food as a source of energy', and 'switching off appliances to save energy'. The textbook quote ignores these alternative conceptions, treating energy as a secure and certain idea in a manner which encourages rote learning of phrases with no connection to the learner.
- Energy is a very difficult and complex idea *invented* by scientists. Arguments about the appropriate way to understand and to teach energy continue in education journals (see the debate between Warren, Schmidt, Lehrman, Hicks, Richmond and others in *Education in Physics* and *Physics Teacher* in the early 1980s). The textbook quote above treats this area as if there were no difficulty in the concept. Many students can feel that their inability to 'see' the world in the same way as the textbook writer means that they are somehow 'blind' or not seeing the world through the same spectacles.

Teachers who are themselves insecure in their knowledge of science can find the uncomplicated transmission of knowledge attractive (Osborne and Freyberg, 1985). Transmissive teaching avoids discussion (since learners lack knowledge worthy of consideration) and interactions which might reveal teachers' uncertain knowledge and so alter power relationships in their classrooms. The view of science as a body of unambiguous right answers for transmission into learners' heads can then trap teachers into a teaching style inimical to their own and their students' learning, or into avoidance of the subject entirely.

A further concern about the consequences of this image of science and good learning is that students who commit the 'facts' to memory are seen to possess a 'natural' ability in science. Other students are given messages that they are not expected to perform as well. Although having a good memory is an undeniably valuable attribute, there is a good deal of evidence that the memorised knowledge is not well understood. Teaching which values a skill that may not be strongly linked to ability in science can alienate the bulk of students from the discipline before they have properly experienced it.

Although this picture is extreme, a great deal of current practice in science teaching conforms quite closely to this picture of the interaction between science content and pedagogy. Fensham (1985) has argued that this is unhelpful to learning in science for all students.

An alternative paradigm

The traditional view of science and consequently of the language of science has been scrutinised, particularly in the last two decades, through considerations of:

- the history and philosophy of science
- the psychology of learning.

This scrutiny has resulted in science being located in a new paradigm (Kuhn, 1970) in which the nature of science and of learning in science is viewed differently. The new paradigm regards science as a human and social construct, and views learning as the personal construction of new knowledge. As a consequence, many of the old securities about the pedagogy of science are seen to be problematic.

Arguments for this new paradigm come from:

- the *history and philosophy of science.* Our perception of the world is seen to be *subjective.* Observations are enmeshed with previous experience of, and existing theories about, the world. We construct meaning for the world around us from our prior attempts to make sense of it. The traditional view of scientific method as the objective scrutiny of hypotheses by reference to unproblematic facts (based on observations) and the consequent rejection of incorrect hypotheses which do not agree with these facts, is now disputed as a description of scientific practice. The alternative constructivist paradigm is less clinical and more human. These are qualities which could well make this view more accessible to young learners.
- the *psychology of learning.* Newer theories see learning as interaction with previously-existing concepts, and as the building of new mental constructs from prior understandings (Osborne and Freyberg, 1985; Driver, 1988). In these new theories of learning there is increasing recognition of the importance of the *affective* dimension in learning; even in the apparently abstract and objective disciplines of science and mathematics (Claxton, 1991). How we feel about the ideas being presented in our learning experiences affects our learning about them. (In this age of concern for animals it would be unwise in the extreme to introduce biology with a programme based on the dissection of small animals!)

Considerations of the importance of *contexts* to learning are allied to this affective dimension. The context in which we learn something affects the way that individuals construct knowledge. Learning about a scientific concept may be much easier through contexts with rich links to students' interests, such as teen culture and the human body (Rodrigues, 1992).

A further complication when considering learning in science is the developing realisation that individual students hold many, often conflicting, concepts about their world, some of which they use in the school classroom, others in the world outside. Within the chemistry classroom students respond that the world is made up of atoms and molecules, but they talk of materials in their 'real world' in quite different terms, denying that blood and skin and wood are molecular, or even chemicals (Happs, 1980). These multiple theories can be used differently depending on *context*. Learners of science who have categorised humans as animals will enter a butcher's shop displaying a sign 'No Animals Allowed' without demur (Bell, 1981). A significant challenge to teachers is to make the science learned in school appropriately available in the real world of the student. Much of the discussion about enhancing learning of science seeks ways to make the content of science more plausible, intelligible and fruitful for learners (Hewson and Thorley, 1989), thus helping them to make better sense of their world. Whilst accepting that this is a very important activity, this chapter argues that some examination of the process whereby science concepts are constructed is also important. The way that constructs are scrutinised, in other words the rules of the game of science, deserves consideration in teaching and learning. If science is a collective construct then exploration of the constraints on this process of construction deserves to be part of classroom interactions.

Constructivist teaching approaches

If students come to lessons with ideas about their world which already make sense to them, then teaching needs to interact with these ideas, first by encouraging their declaration and then by promoting consideration of whether other ideas make better sense. These procedures have been outlined in the generative teaching approach of Osborne and Freyberg (1985) and the interactive teaching approach of Biddulph and Osborne (1984) and further discussed in Driver (1990).

A feature of this approach to science teaching is that the outcomes can be different for different students. Some may want to explore a concept in considerable detail and will develop understandings closer to those of the scientist, while others will be more interested in exploring practical and personal aspects of the topic. This diversity of outcome poses problems for teachers. The outcome from traditional science lessons is also diverse, though assessment procedures that rely heavily on recall and rote learning conceal them. When understanding is probed at a deeper level the learning is often found to be superficial, even for students who have been described as very successful. The problem for learners who *are* described as successful is that they are often unaware of the partial nature of their development of a particular concept, and find difficulty in contemplating change to their ideas. Procedures in which there is more conversation about learning provide a better base for further learning. The open negotiation of meaning, and appreciation of the partial nature of the learning achieved, also model a better image of science.

The process of developing science content in constructivist teaching

Rather than discussing constructivist teaching in a generalised manner, the remainder of this chapter refers to three topics, *floating and sinking*, *energy* and *photosynthesis*, and considers some possible references to the process of science which could be introduced when these are the focus of learning in the classroom. The discussion draws on research into teaching and learning about these concepts, particularly that reported in Biddulph (1983), Osborne and Freyberg (1985) and Carr, Hayes and Symington (1991) on floating and sinking; in Carr and Kirkwood (1988) on energy; and in Barker and Carr (1989) on photosynthesis.

Floating and sinking is an appropriate topic for detailed consideration since it is a common topic in primary science programmes, often assumed to provide no particular problems for learners (the New Zealand Minister of Education recently stated that knowing that heavy things sink is a significant beginning to early learning in science). Energy is another concept introduced to primary school students; the argument being that a fundamental concept in science should be introduced in a simple manner at an early stage in learning. Photosynthesis is also seen to be a fundamental concept, most commonly introduced through the notion of plants using energy from the sun to make their own food; a notion that has a number of difficulties for learners.

Teachers reflecting on their pedagogy could usefully consider five questions as they develop their teaching approaches and reflect on student learning. These are:

- does nature contain a definition of the concept which can be uncovered through appropriate experiences?
- how does science develop a statement of a concept?
- is there a single explanation for a phenomenon which teachers should aim at?
- can science always provide an answer to a question?
- when a 'better' explanation is proposed how do scientists decide to accept it?

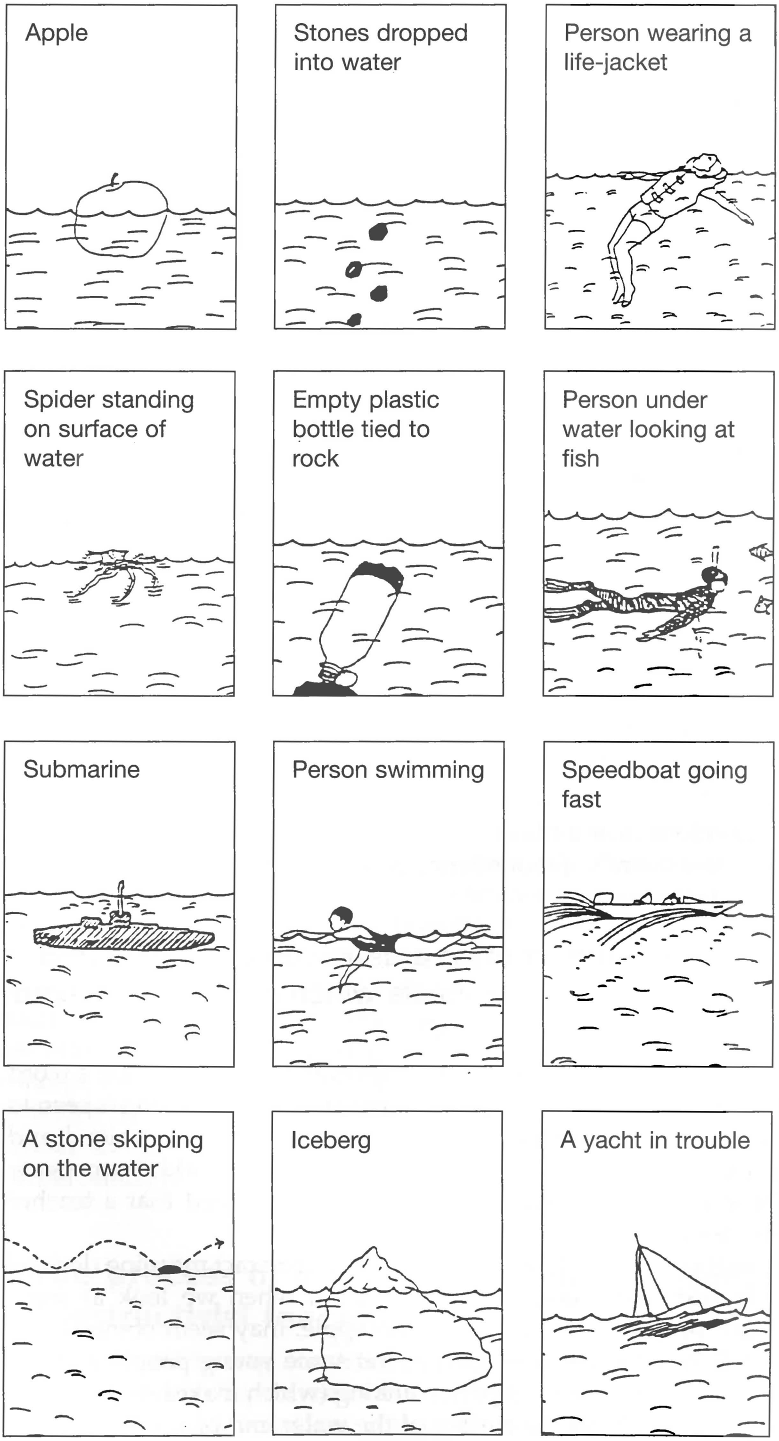
These five questions raise a number of important issues about the concepts in science and consequently about science pedagogy. The following sections consider each in turn.

Question 1: Does nature contain a definition of floating and sinking, energy, and photosynthesis which can be uncovered through appropriate experiences?

The implied view of much science writing in texts and teaching is that a word such as floating has a *meaning which exists in the world.* This meaning is seen to be independent of people, unambiguous, and apparent to the trained and careful observer. Through a process of exploration of their world, learners are expected to unearth this *true meaning* of the word, provided that a teacher guides the process with skill.

The word 'floating' does not, however, seem to have exact meaning derived unambiguously from experience. This is apparent when we look at some instances (Figure 14.1). The first example, the apple, may seem obvious and uncomplicated. Surely the apple *is* floating. Yet some young people will say that the apple is partly floating and partly sinking (which makes sense if your idea of floating is to be above the surface of the water and of sinking is to be

Figure 14.1 Instances and non-instances of 'floating'



below that surface). If the illustration of the stones dropped into water showed one of the stones partly above the surface then the logic of this view could be that some of the stones are sinking but that one is floating. Consider the person under the water looking at fish. Is the person floating? If our concept of floating is that something is to be *above the surface of the water,* then the answer is no. If we know that an apple pushed under water will bob up again when we release it we may decide that floaters can be submerged temporarily, but that they remain floaters. How would this affect our response to the survey question about the underwater swimmer? We know that divers can swim back to the surface, unless something goes wrong (and the person illustrated does not look distressed). By this argument perhaps the person is floating. Another view of floating involves the common experience of feeling *supported by the water.* From this viewpoint the diver is floating, even although submerged. The same considerations apply to the submarine. Further complexities arise when we turn to the yacht in trouble. In our normal use of language the yacht is sinking but in the illustration it is still floating, if only just! The person swimming may set off different associations depending on our own experiences. For some people water is a dangerous environment, raising fears of drowning. This illustration then shows a person who is going to drown if he/she stops swimming. Other responses may arise from a personal experience of comfort in the water, knowing that when you cease swimming you can float. Each association could lead to a different response. The person swimming has introduced a puzzling new dimension, that of movement. The same problem applies to the stone skipping along on top of the water. We know that most stones would sink if they stop moving (in a country like New Zealand where pumice is often found there are stones which float!). Does that mean that they are floating? The same difficulties apply to the speeding boat.

Complications seem to be piling up endlessly but the point to make can now be stated clearly. The idea of floating does not exist sharply defined in nature. We need to construct a meaning for it – which is just what scientists have done. Their concept of floating and sinking refers to many experiences, and tries to make their observations more coherent. In the process, they have invented concepts which at times they have agreed to change. This is a good description of science, and one we argue should be shared with learners as their learning in science is developing.

Similar considerations apply to the concepts of energy and photosynthesis. As learners (both students and teachers) explore their concepts, they will find that there are a number of conflicting ideas (concepts of energy may centre on food, and on people having or requiring energy). Conservation of energy is a difficult construct when prior ideas strongly support the need for continual supplies of food to keep one's energy up, and, paradoxically, when people exercise vigorously to build up their energy! Prior ideas related to photosynthesis are also likely to require consideration. The concept of plants making their own food from the energy of the sun contains many pitfalls, particularly when it is commonly held that plants get their food from the soil, and the idea of invisible gases providing the substance from which plant material is constructed has so few links to prior experiences.

There are, then, no definitions of these concepts to be uncovered by appropriate experiences. Rather, each construct is gradually made from many instances, and its power is dependent on bringing together many related ideas.

Question 2: How does science develop a statement of a concept such as floating and sinking, energy, or photosynthesis?

The survey on floating and sinking provides clues to the answer to this question. Development of a construct of floating first confronts the complexity of our rich world of experience. Scientists, for very good reasons, aim to reduce this richly complicated world of experience to a more manageable, tidied-up one. For science to 'work', concepts are sharply focused on aspects chosen to be relevant and reproducible. Paradoxically this process leads to concepts which have very great power in making predictions about the world, and this is the 'pay-off' which has made science one of the great human inventions.

In the case of floating and sinking, the scientists' construct first seeks to make these two possibilities mutually exclusive (something is *either* floating *or* sinking, and ambiguities such as partly floating and partly sinking, floating now but about to sink, are avoided). The iceberg, then, is viewed by science as floating, even though many people will tell you that the part below the water is sinking and the rest is floating. The *total system* is defined as an instance of floating. By reducing the complexity of the real situation, simpler and tidier statements can be made. The person in a life-jacket provides a further illustration. We might think that the person is sinking and the life-jacket provides support so that the sinking person can float. Again by treating the system as a whole, science chooses a simpler more reduced view of the world. So the first strategy is to treat systems as a whole. A similar decision about defining a system needs to be taken when energy is the focus of teaching and learning. Many of the problems associated with this topic are clarified by clearly defining a system and a change to that system. Students were often unsure whether to remove the human operator from systems. Switching on a light implied the use of muscles, and before objects could be dropped they had to be raised or pushed by a person (Carr and Kirkwood, 1988).

The next decision about floating is to shift the focus from the surface of the water. The new construct considers something to be floating if it is *supported* by the water (even if it is under the water). This extends the concept to more situations. The yacht in trouble is therefore considered to be floating since it is still supported by the water. This example provides a further instance of the way that meanings for concepts are constructed in science. The situation is treated *as it is at the moment*, regardless of what may happen next or what may have happened before. Science often takes this view of the world, disregarding the past history of an event, and any possible future. This provides a sharper focus, even though information from our prior knowledge is now ignored. Of course, in everyday language the yacht *seems to be* sinking (though some can float like this for days), but the scientists' construct is that at the moment it is floating. It is valuable to think about how this construction of meaning does not always remove some difficulties. Consider now the empty plastic bottle tied to a rock. The bottle is described by science as *floating* although many people would describe it as sinking or sunk since it is beneath the water. Is the scientists' response based on the understanding that if the bottle is released it will float to the surface? This is not the case. The scientist is not using knowledge of what might happen in the future. The decision is based on seeing the bottle as being supported by the water (experiencing an upthrust) and therefore *floating*. This reduction to a simpler, more extended concept is typical of the process of science. Indeed, the concept of floating and sinking has been extended by science to liquids and gases other than water. Focusing on the moment and using the concept of support provides a more powerful idea. By this process science has been developed as an interrelated set of constructs about the world, in which carefully defined ideas work together to inform us about much of our experience of the physical world. When scientists decide to confer onto a word a particular, more exact definition, this is an act of construction from the world of experience significant to scientists. The process of teaching and learning ought to engage with this 'rule of the game' and its consequences.

The concepts of energy and photosynthesis have also been constructed by selection and reduction from the world of experience and of ideas, and their modern meanings are powerful because of this. Realisations that different phenomena such as heat, electricity and mechanical work could be quantitatively interconverted led to the invention of the concept of energy and of its conservation. Photosynthesis is an elaborated concept which depended for its clarity on unravelling of the concept of gases, as well as the development of the concept of energy. The power of the ideas has a great deal to do with their connectedness, which is why teaching can not expect successfully to develop the concepts from a single experience or a few isolated experiences. Neither can teachers expect to help students change their concepts without deliberate explorations of their connectedness.

In the process described above, science has often reinterpreted experience and as a result the words of science have changed their meaning. Consider the word 'atom'. This word has been used in science since the ancient Greeks. Their concept of atom held that all substances were formed of their own particular atoms (there was an atom of milk, an atom of blood, an atom of glass and so on). Each substance was made up of a large number of similar atoms; the concept implied that there was a very large number of different atoms. Later the word atom came to mean an unbreakable unit of matter, and substances could be compounded of several different atoms. The number of possible different atoms was consequently greatly reduced. It was difficult to decide how many distinct atoms there were, so elaborated rules were constructed to decide this. Eventually the construct, atom, became very sharply defined and scientists could state that all materials were made from a defined number of them. Since that time of certainty the picture has clouded.

The discovery of isotopes and of elements beyond uranium required that the construct be changed. More recently, quantum theory has necessitated a further reconstruction of the word. Science no longer defines atoms as the indestructible building blocks of matter since many sub-atomic particles have now been defined. The point being made here is that the concept atom does not exist out in the world somewhere waiting to be discovered; the word is undergoing a process of continual revision of meaning in the light of further explorations of the world.

This reduction of the world to manageable aspects should be understood for what it is. Rather than science being thought of as a 'given' feature of the world around us, the learner needs to appreciate that science has been *constructed by people* as a way of making better sense of the world.

This has obvious implications for science teaching and learning. If science develops by taking decisions about what would make better sense of the world, then teaching approaches could describe this procedure candidly and at a level appropriate to the learners' knowledge at the time.

Scientists, then, deal with an idea such as floating and sinking by tidying up the world and then inventing powerful ideas to make better sense of it. This process involves conscious building of new ideas from prior knowledge. There is a tension here between reducing the world to 'manageable' simplicity and then treating systems as a whole. A vital debate about the difference between Western science and other means of knowing would be informed by students being aware of this tension (Christie, 1991).

Question 3: Is there a single explanation for the phenomena of floating and sinking, energy, and photosynthesis which teachers should aim at?

A common view of science is that there is a single scientifically acceptable description or explanation which teachers need to instil in their students. This is frequently apparent when teachers talk about how they should never tell their students anything that is wrong, and that the end result of any sequence of lessons is to produce the right answer. This encomium places an impossible burden on teachers, one which some are not aware of. School science can only be provisional knowledge leading towards the scientist's construct. In most cases this scientist's concept is inaccessible to students but transitional concepts can be valuably addressed. Preparedness to acknowledge the provisional nature of their learning and to accept that future change will be necessary may be a very valuable part of science teaching and learning. If we consider the concept of floating and sinking, the following explanations of why an apple floats are useful provisional concepts for learners from which the scientist's concept could be developed.

The apple floats because:

- it is light for its size
- it is held up by the water
- the upthrust of the water is equal to the weight of the apple
- the weight of the water displaced is equal to the weight of the apple

- the apple's density is less than the density of water
- the difference in water pressure below and above the apple results in a net upward force equal to the weight of the apple.

The level of explanation depends on the purpose of the exploration and the background of the person for whom explanation is being provided. It is inappropriate for classroom interactions to convey the impression that there is a single correct explanation of any phenomenon or a single definition of any concept. This is a challenge to the pedagogy of most teachers.

Question 4: Can science always provide an answer to a question?

There are at least two instances in the survey which test the scientific view of floating and sinking to the limit; the spider standing on the surface of the water, and the stone skipping on the water. Indeed, these exemplars remind us that in the current description of phenomena, 'floating' and 'sinking' are inappropriate terms for their analysis. The two instances show a water surface and objects associated with it, yet we have real difficulty in answering the question 'Is the object floating?' and *so does the scientist.* Some scientists would say that the spider is floating because it is supported by the water. Others would say that the phenomenon involved here is surface tension and that the spider is not floating but rather supported by a 'skin' on the top of the water. We can support a needle on a water surface by carefully lowering it onto the surface, but this needle will sink if the surface is disturbed or some detergent is added to the water. The concept of floating held by most scientists requires that water is displaced, but in the case of the spider this may be said not to have happened.

What about the stone skipping on the water? This is a tricky one since the movement of the stone is vital for it to remain on top of the surface. When its speed drops sufficiently the stone will sink. Science *cannot answer the question* 'Is the object floating?' in the spirit in which it was asked, even though it looks like a perfectly reasonable one. (There are similar problems with the speedboat, though in this case the boat may well float if it stops moving). The scientific idea of floating and sinking is embarrassed when objects are in motion because the idea then becomes too complex for a straightforward analysis.

The implications of this for teaching are clear. Young learners are very likely to ask questions which do not fit tidily into the constructs of science even though they seem simple. The apparent simplicity of the language conceals a very difficult problem. A teacher who understands that science does not have all the answers may feel more comfortable about helping a student to explore the world than the teacher who feels threatened by challenging questions. It should not be considered unprofessional for a teacher to acknowledge that some questions are unanswerable at the level of knowledge of science of the learner. This issue becomes clearer through some other examples of apparently simple questions, like: 'Is there more energy in a glass of milk than a glass of water?'. The proper answer to this question is that there is insufficient information for an answer to be given. We need to know what happens next. As already discussed, the nature of science is to exclude from the system past history and future possibilities. In this case there are a number of possible futures. If the glasses are drunk then one analysis applies; however, if they are thrown at something then the analysis changes. The question can be answered but only when more information is provided. Again a simple question, posed in apparently exact terms is one which cannot be answered. Questions like this can be good questions for exploration of basic understanding.

The last question comes to the heart of the construction of ideas in science, since it explores the process of change in the constructed meanings of ideas.

Question 5: When a 'better' explanation is suggested, how do scientists decide whether to accept it?

If science is not a set of truths which exists independently of people then in the construction of this structured complex of ideas there will often need to be *changes* made to ideas. This process of changing prior ideas is also the core activity of education so the issue of acceptance or rejection of a new idea is an important one both for science and for science education. We now know that learners often retain their prior meanings for words rather than taking on new meanings and we also know that this situation is often not apparent to the teacher. If your idea of floating was based on an object being above the water surface, then introduction of the 'better' idea that floating involves support by the water will have caused problems. You would need to have explored the new idea and found it to be more helpful and to offer better explanations before you would feel comfortable with it.

Scientists have frequently had to face this difficulty. Although a popular image of scientists is that they quickly accept new discoveries, the history of science shows that many scientists have continued to disagree with developments in their field for very long times (one commentator on the history of ideas has remarked that new theories in science are finally accepted when the last opponent dies of old age). When an idea has become part of the way that you think about the world, changing that idea will mean overcoming barriers which can be very difficult to break down. Nevertheless, there are some 'rules of the game' of changing ideas that can be offered. They have to do with new ideas being:

- more parsimonious (if a single explanation encompasses several others then science tends to prefer the more inclusive)
- more elegant and coherent (if the new idea is tidy and links to a greater number of other ideas then it will be preferred)
- able to explain what is already known and also to predict some unknown outcomes. Ideas are preferred which have explanatory and predictive power.

There can be valuable debate over these statements. The point made here is that addressing them would assist learners and teachers to explore the process of the construction of scientific knowledge. Much of the current critique of science and its products does not confront the nature of science and the procedures used in its construction. The best criticism comes from understanding these rules, followed by an analysis of their consequences. Many of our students reject science without any understanding of the power of its constructs and the manner by which these have been constructed.

The important point for our discussion here is that when teachers are encouraging students to adopt a *different* construction of a concept, classroom activities require more than statements which outline the new meaning, perhaps followed by some exercises. Learners need time to consider their prior meanings, to explore new ideas, to link them to other existing ideas, and to construct new meanings knowing what the requirements are for this reconstruction. The false view of science which holds that scientists are rapidly converted to new ideas has resulted in classroom approaches to science which too often assume that changing ideas is an easy procedure. The most important feature of an approach to science classes which addresses the difficulty of changing ideas is *conversation.* Science lessons which continually seek learners' ideas, which help to clarify them, and which provide an open and unthreatening environment for changing these ideas through conversation are classes in which learning in science can be improved. The false idea that science is exact and therefore that concepts in science are unproblematic can be argued to have trapped science teaching into a pedagogy which misrepresents both the content of science and the process whereby this content is constructed.

Summary

This chapter argues that classroom teaching and learning should address the processes of constructing and reconstructing scientific knowledge. A number of issues arise naturally in the classroom which enable teachers to explore the nature of science. These include:

- how, by building up experiences and trying to make better sense of them, scientists construct concepts – which are not 'out there' in the world waiting to be uncovered
- how science takes the richly complex world of experience and reduces it to a more manageable one in order to make more powerful statements
- how science often focuses on a defined system as it is at the moment and ignores previous history or possible futures unless these are clearly stated
- that there are a number of apparently simple questions about the world that may be very difficult for science to answer
- that the rules for deciding that a proposed explanation is better include notions of elegance, parsimony and greater connectedness as well as those of plausibility, intelligibility and fruitfulness. The process of making a substantial change to the ideas of science is one which has aroused and continues to arouse argument and even passion.

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