Students’ learning in science: implications for pedagogy and the curriculum

Abstract

This paper offers a framework for how learning in science takes place. It describes learning as an active process carried out by the learners and leading to the gradual development of broad big ideas from smaller ones. It draws out some implications for pedagogy and for the curriculum.

Introduction

There are two threads running through this paper which are best explained at the start. One is the assumption that a key aim of science education is students’ understanding, not merely being able to repeat facts and memorised knowledge. So it is necessary to be clear about the meaning being attached to understanding. The second thread concerns the development of understanding in terms of a progression from ‘small’ to ‘big’ ideas: ‘small’ referring to ideas about particular events or objects; big ideas explaining a range of related events or objects.

How something is understood can vary considerably according to context. As White (1988) points out, understanding ‘is not a dichotomy and is not linear in extent’ (p52). The understanding of a phenomenon, such as dissolving, of a primary school student and a higher education science student will be different but both may meet the expectations appropriate to their stage of learning. What is probably the same for both is that the ideas they have make sense to them and fit the experiences they need to understand at a particular time. As the younger students’ experiences expand and their ideas no longer provide a satisfactory explanation, so the phenomenon will need to be understood in a different way. Progressive understanding that accompanies expanded experience can also be seen as the development of successively big ideas. Small ideas are context-bound, whilst ideas that are widely applicable are necessarily content-independent. For example: ‘an idea of what makes things float can be used for all objects and all fluids. To move from an idea of why a particular object floats in water to the big idea of floating is a large step which involves seeing patterns in what happens in very different situations’ (Harlen, 2010, p 26).

Early ideas

Understanding, for any learners, can only be achieved through their own mental activity. It is only ideas that make sense to the learners that they can use in explaining objects, phenomena and events in the world around. We know this from our own experience. We also know, from research, that students make sense for themselves of the phenomena and events they encounter, but the understanding they arrive at in this way may not be the same as that arrived at through a scientific approach. For example, students often have their own explanations for how we see, how plants feed and grow, why the Moon appears to change shape, etc. These ideas are often different from the scientific view.

We now know a great deal about students’ ideas from research in the past 40 or so years. Earlier work, following on from that of Piaget, showed that it was clear that children form ideas about the
world around without being taught, but more is now known about the nature of these ideas. There is rich learning before the age of one year, when infants begin to notice patterns in the objects and events around them. Duschl et al (2007) conclude from a review of research with infants that ‘Beyond just tracking those regularities, however, they also come to link them to broad domains, such as those corresponding to physical, mechanics, cognitive and motivational processes, matter, the living world and cosmology’ (p 82). This does not mean that these young children develop broad ideas within these domains but rather distinguish between, for instance, animate and inanimate things and different kinds of materials. Indeed, a key characteristic of children’s early ideas is that they are context-dependent. Children typically develop an explanation for a phenomenon in a particular context and a different one for the same phenomenon in a different context. (For instance, the reason for the loss of water from an open container of water and from wet clothes drying by a heater). They do not seem to develop alternative conceptions in the form of generalisations. So the task of developing better explanations is, on one hand, to help children to consider alternative explanations for particular events and, on the other, to help them link these small ideas into bigger ones which fit related events in different contexts.

Challenging particular explanations is perhaps easier than taking on broadly based alternative theories or misconceptions. But it also argues for early action, since students will begin to form their own bigger but non-scientific ideas as their experiences broaden. Research shows that, if these ideas go unchallenged, they can interfere with the development of more scientific understanding. At any stage, however, this understanding must be developed through the students’ own mental and sometimes physical activity and starting from the ideas they have worked out for themselves.

Other features of children’s own ideas underline the difference between the ‘common sense’ approach, largely based on perception, which they use in forming their own ideas, and the often counter-intuitive scientific ideas. They perceive that moving objects generally stop moving apparently by themselves and so find it difficult to understand that a force is always necessary to change motion. They make judgments about size of things and how heavy they are from how they appear and feel, which causes difficulty when appearances change radically. In such cases children need direct help to consider alternative explanations for what they observe and to learn how to measure different quantities. This does not mean putting children’s own ideas aside, but giving them alternative ways of making sense of what they observe, which they are unlikely to consider on their own. This has implications for pedagogy, as discussed later.

A model of the development of bigger ideas

From observation of children and adults, including scientists, in daily life, solving a problem or trying to understand a new experience begins by linking it to some previous experience and the ideas that explained it. So the first step in understanding what is going on is creating a possible explanation (hypothesis) based on ideas brought from previous experience. Scientists and others working scientifically then proceed to see how useful these existing ideas are by making a prediction based on the hypothesis. Ideas that are really useful will be able to explain related phenomena and it will be possible to use them to make predictions. To test a prediction, new evidence about the phenomenon or problem is gathered, then analysed and the outcome compared with the predicted result. To be more certain of an explanation it will be desirable to make and test more than one
prediction, so there may be several iterations of the prediction to investigations to interpreting data loop (Figure 1).

From the results, a tentative conclusion can be drawn and compared with the possible explanation. If it gives a good explanation of a new phenomenon then that idea is not only confirmed, but becomes more powerful – ‘bigger’, because it now explains a greater number of phenomena. If predictions based on a suggested idea are found not to be supported by evidence, then a different idea needs to be tried. However, knowing that the existing idea does not fit is also useful. Different ideas to try can be suggested through discussion with peers who may have different experiences and related ideas, through consulting various resources and in the context of the classroom by the teacher offering ideas as worth trying rather than as ‘the right answer’. What this model describes is not a process which is consciously pursued step by step. It may happen in a flash or over an extended period of time. Imagination and creativity have a role as well as rationality.

Figure 1

This process of building understanding through collecting evidence to test possible explanations in a scientific manner offers a view of how smaller ideas are progressively developed into big ideas. In doing so, it is important to acknowledge, and to start from, the ideas the students already have, for if these are just put aside the students will still hold onto them because these are the ones that they worked out for themselves and make sense to them. They must be given opportunities to see for themselves which ideas are more consistent with evidence.
However, the development of understanding in this way depends on the processes involved in making predictions and gathering evidence to test them being carried out in a scientific way. Students, particularly young children, do not instinctively use these processes. They may not test their initial ideas and when they do they may not do it scientifically. Their existing ideas may influence what is ‘observed’ through focusing on certain observations that confirm their ideas, leaving out of account those that might challenge them. Children sometimes make ‘predictions’ that they already know to be true and so are not a test of an idea. In setting up a test they may not control variables that should be kept constant. When these things happen, the ideas that emerge are not consistent with evidence: hence the importance of helping them to develop the skills needed in scientific investigation.

Even when children are capable of using these processes in some circumstances, they do not necessarily do so in others. Indeed, there is plenty of evidence that knowledge of the subject matter under study has a strong influence on the use of these processes. To some extent this is obvious, since it might be expected that familiarity influences recognition of what variables are likely to be relevant in an investigation. So even a young child might be able to plan a ‘fair test’ of how well balls bounce on different surfaces but not be able to plan a fair test of something much less familiar to them, such as how the concentration of a liquid affects its osmotic pressure. In other words, the way in which the processes are carried out crucially influences the ideas that emerge. But at the same time the content can influence the use of process. This complex interaction of process and content means that conceptual understanding and skills of investigation and reasoning need to be developed together.

**Implications for pedagogy**

Pedagogy means not only how teaching is enacted but the theories, values and justifications for these actions. How teachers teach is strongly influenced by their views of how students learn, of the nature of the subject matter – in this case science – and of the goals of learning which are valued (as indicated, for instance, by what is assessed.)

**Understanding of how students learn**

The view of learning outlined above clearly implies a constructivist pedagogy, which involves:

- helping students to understanding phenomena in a more scientific way, starting from the ideas that students bring from their previous experience
- enabling students to take an active part in creating their scientific understanding
- helping them to consider alternative ideas to their own through access to resources and discussion with others
- engaging them in discussion, sharing, dialogue, defending and reflecting on their ideas.

A view of learning as taking place in the heads of learners also implies a pedagogy that has much in common with formative assessment. The aim of using assessment formatively is to enable students to take ownership of their learning – one of the key features of genuine understanding. It extends the notion of taking students’ ideas into account, applying it not only as a starting point but as an ongoing process throughout learning activities. The formative use of assessment is a continuing cyclic process in which information about pupils’ ideas and skills informs teaching and helps learners’
active engagement in learning. It involves the collection of evidence about learning as it takes place, the interpretation of that evidence in terms of progress towards the goals of the work, the identification of appropriate next steps and decisions about how to take them.

Formative assessment helps to ensure that there is progression and regulates the teaching and learning processes to ensure learning with understanding, by providing feedback to both teacher and student. Helping students to recognise what are the learning goals of their activities and the quality criteria to be applied enables them to assess where they are in relation to the goals. This puts them in a position to identify, with their teachers, the next steps in their learning and to take some responsibility for progress towards the goals. The role of teachers in using assessment in this way is not only to find out where students are in relation to the goals and to provide activities with the right amount of challenge to advance their existing ideas and skills, but to share the goals with students and help them assess their own progress towards them.

The recognition that students are the agents of their learning is also central to the notion of pedagogy described as inquiry which has given rise to the widely supported notion of Inquiry-Based Science Education (IBSE). This term has a range of meanings both in theory and practice, extending from what is characterised as being ‘hands on’ to what involves a complex pedagogy embracing a constructivist view of learning, the application of formative assessment, scientific argument and reasoning about evidence. Some definitions have focused on the processes of gathering and reviewing evidence (NRC 1996), whilst others connect this with the development of understanding, for example:

Inquiry teaching leads students to build their understanding of fundamental scientific ideas through direct experience with materials, by consulting books, other resources, and experts, and through argument and debate among themselves. (NSF 1997:7)

This statement includes a claim that has not yet been substantiated by a body of research. As in the case of most innovations, in the hands of committed and well-prepared teachers it can lead to learning gains (Dochy et al (2003). However, the popular focus on processes causes growing concern that use of inquiry skills alone does not develop key concepts. As forcefully pointed out by Millar and Driver (1987), there is nothing specifically characteristic of science in processes such as making observations, posing questions, planning investigations, and so on. What a process-oriented view of scientific inquiry leaves out is that its purpose is to seek explanations, to answer questions about the natural world. It can lead to ‘doing for the sake of doing’ rather than for the sake of learning (Barron and Darling-Hammond 2010). Scientific inquiry not only requires that the activity concerns some recognisable science content but that it leads to ideas that develop understanding of scientific ideas and of the meaning of scientific activity. This is not to deny the value of developing critical thinking, problem-solving, creativity, independence and positive attitudes towards school, but to point out that unless inquiry-based activity also develops key concepts underlying a discipline, students will miss opportunities to build understanding that is needed to tackle new problems, undertake new inquiries and take decisions.

Understanding of science
How teachers teach is affected, perhaps unconsciously, by how they understand scientific knowledge to be created. One view is that science is developed mainly through a process of deductive reasoning, created by scientists building and testing theories and models. The outcomes of this process, if repeatedly found to agree with existing evidence, become accepted as currently understood facts. Ideas that provide explanations across a range of phenomena become theories. Regarding scientific knowledge as being created by testing ideas is consistent with concern for the ideas that students bring to their science activities. It will lead to attention being given to testing the predictions generated from these ideas.

An alternative to this view is that of modernist science in which hypotheses and predictions are generated from observations. It is based on the fallacy that observation is theory-free, whereas it has long been pointed out that all observations are directed by expectations derived from existing ideas (Popper, 1959). The view that regards knowledge as emerging from objective observations is expressed in terms of ‘discovery’, implying that there is a ‘truth’ to be discovered if only we are wise, diligent and lucky enough to find it. It leads to the belief that learning science is a matter of finding ‘right answers’. This conflicts with the description of the work of scientists as constructing knowledge about the world around, which is accepted as long as there is a consensus that it fits available evidence.

Pedagogy based on a view of learning in science mainly as a process of deductive reasoning starts from the students’ existing ideas. The use of the word ‘mainly’ here acknowledges that extreme positions are untenable and that in practice both inductive and deductive reasoning will be used since ‘the process of theory development and testing is iterative, uses both deductive and inductive logic, and incorporates many tools besides direct experiment.’ (Duschl et al, 2007: 27)

But science is more than a body of facts and theories. It has been described as multifaceted (Lehrer and Schauble 2006), the facets including knowledge about the natural world, a questioning attitude, a process of logical reasoning about evidence and a process of participation in scientific activity. It is not difficult to see that the multifaceted nature of science requires a multifaceted pedagogy. There will therefore also be a place in science education, at one time or another, different approaches, including:

- Problem-solving
- Structured activities focusing on parts of investigations such as planning or interpreting data
- Direct instruction in matters such as procedures, conventional representations, names, use of equipment
- Application and integration of concepts as they are developed
- Modelling relationships, physically and mathematically, to gain conceptual understanding of the concepts and principles involved
- Extended inquiry in which many of the above are included.

Implications for the curriculum

The word curriculum has many meanings. It is used in various contexts to refer to: the written document that presents what it is intended students should be taught; what they should know or be
able to do; what is actually experienced by students; what they actually achieve. The National Curriculum (DfEE, 1999) sets out both what students should be taught and what they should learn, one often repeating the other. This seems to conflict with the view expressed in the recent White Paper:

The national curriculum should set out only the essential knowledge and understanding that all children should acquire and leave teachers to decide how to teach this most effectively.
(DfE 2010, Para 4.1)

Although what ‘all children should acquire’ could be interpreted as what they should be taught, making a distinction between what and how they are taught, it could equally be interpreted as meaning that the written curriculum ought to indicate only the goals of learning. Lack of clarity on this point is a result of insufficient dialogue between the profession and policy-makers about what a national curriculum should be, what it should do for teachers and how it should be structured. The discussion here is focused on the implications of how students learn for the learning goals and how they are expressed.

Learning, as represented in Figure 1 and discussed earlier, noted the interdependence of the skills and processes involved in developing gradually bigger ideas. Understanding, it was argued, depends on ability to gather and interpret evidence yet, at the same time, the ability to gather and interpret evidence is influenced by the conceptual demands of the subject matter.

Two points follow from this. First, that learning with understanding requires both the development of inquiry skills concerned with use of evidence and the development of concepts so that these two aspects of learning science, at least, should be included in the curriculum. Second, that there needs to be a progression within statements of the conceptual understanding expected so that students at different points in their development can achieve understanding through their own thinking. If too great a step is required students fall back on rote learning without understanding. While the necessary matching to the development of the students’ skills and concepts is ultimately dependent on the teacher, the curriculum should provide a framework which facilitates appropriate planning decisions.

The question of whether it is necessary or even possible to express the goals of learning as statements which combine inquiry skills and concepts requires clarity about the purpose of a (national) curriculum document. If this is, as suggested above, to set out the goals, not how they are to be achieved, then it is not appropriate for it to be concerned with the relationship between different kinds of goals. That is the business of curriculum materials and non-statutory advice.

The curriculum should, however, indicate the lines of progression in the facets of science that it includes. The progressions should not be in terms of a sequences of activities, but a broad description of what might be expected at various points as students move from pre-school, through primary and secondary education. Identifying these progressions requires both logical analysis to find the simpler ideas that are needed as a basis for more complex ones and empirical evidence from research (Harlen et al 2010). It would provide teachers with an account of the small ideas and show how these are followed by bigger ones which can help students to explain a wider range of
experiences and then merge into the more abstract ideas that enable understanding of phenomena and relationships across a range of experiences.

**Conclusion**

Understanding how children learn has a fundamental role in helping learning. It enables teachers to provide experiences that take students’ own ideas as starting points in developing their understanding towards more scientific and progressively bigger ideas, as set out in the curriculum. The learning activities should be chosen by teachers in the knowledge of how each contributes to the development of these ideas.

**References**


Harlen, W (Ed) (2010) *Principles and Big Ideas of Science Education*. Hatfield: ASE.


Wynne Harlen

March 2011