Knowing is only the first step: strategies to support the development of scientific understanding

Richard Brock

ABSTRACT Acquiring knowledge about science is an important part of developing scientific expertise. However, students can know many facts about science and yet fail to achieve highly on certain kinds of assessments, or to feel that the subject is personally meaningful. The concept of scientific understanding is examined to explain the gap that exists between knowing about science and successful learning. Models of scientific understanding suggest a number of strategies to support science learning that go beyond acquiring knowledge. It is argued that acquiring scientific knowledge is the first step in an extended process of developing understanding.

Students sometimes perform poorly on assessments because they lack the required knowledge. A student may not know the equation for photosynthesis or may be unable to recall the order of metals in the reactivity series. Such gaps in knowledge are not always easily overcome, as students may not possess strategies for successfully retaining information or they may lack the motivation to engage with the material. However, at least in principle, the strategies a teacher should use to assist these students are clear: strategies to boost motivation should be implemented, the target knowledge retaught and approaches for its retention introduced to the student.

Beyond such deficit cases, a more challenging category of learner exists: students who have successfully learned much of the required knowledge yet struggle to perform as expected in certain kinds of assessments; that is, students whose difficulties do not arise from a lack of knowledge. Consider the cases below:

- the student who can state many of the key knowledge elements in a topic from memory, yet performs poorly in homework and assessments;
- the student who has completed problems in class successfully but comments that the questions in an examination were unfamiliar and challenging to complete;
- the student who had appeared to be a successful learner at one stage of their academic career but who finds their approach to learning no longer leads to high achievement at a later stage.

Keith Taber (2005: 224) has drawn an analogy between the roles of teachers and doctors by arguing that teachers should seek to identify and remedy the causes of students' learning difficulties, much as doctors diagnose and treat illnesses. He describes four 'learning impediments' that may cause a student to fail to learn the target knowledge, only one of which is the result of a lack of knowledge:

- **deficiency learning impediments** – a learner lacks necessary knowledge of a topic;
- **fragmentation learning impediments** – a learner possesses relevant knowledge but fails to activate it appropriately or to make connections with pre-existing knowledge;
- **ontological learning impediments** – a learner misclassifies knowledge, for example, heat is categorised as a substance;
- **pedagogic learning impediments** – a learner develops invalid ideas through teaching, for example, that ionic bonding requires electron transfer.

One goal of science education is to support students to develop representations of scientific concepts in long-term memory. However, the acquisition of such knowledge is a necessary but insufficient step on the path towards another significant aim of science education, the development of scientific understanding. The next section considers different interpretations of the concept of scientific understanding.

Models of understanding

A number of different models of scientific understanding have been developed (de Regt, Lionelli and Eigner, 2009). First, understanding has been linked with an appreciation of the relationships between knowledge elements (Kvanvig, 2003). Several descriptions of scientific understanding emphasise that understanding goes beyond simply knowing facts about science (Baumberger, Beisbart and Brun, 2017), for example, a student may be able to define various concepts in dynamics, such as velocity and acceleration, but be unable to relate them together to develop an explanation of motion in a given context.

Second, understanding has been linked to the development of mental models (de Regt *et al*., 2009). A mental model might be thought of as a psychological simulation of a situation that a student can 'run' in order to make predictions. For example, a student with an effective mental model of the motion of particles in a balloon might be able to suggest how changing its temperature affects pressure and volume and might be considered to have some understanding of the relationship between variables in this context.

Third, understanding has been linked to the possession of certain kinds of knowledge, for example, knowledge of cause and effect relationships (Lipton, 2004) and tacit knowledge, knowledge that is not directly expressible in words (Brock, 2015). Causal knowledge is particularly significant in science education as many, though not all, scientific explanations are expressed as a relationship between a cause and an effect. Causal knowledge is needed to represent the mechanisms underlying phenomena. For example, a learner who knows the causal relationship between resultant force and acceleration has some understanding of the Newtonian model of motion. However, only some of the knowledge a learner possesses is explicit, that is, expressible in words. In particular contexts, a student who understands and a student who fails to understand may possess similar explicit knowledge (Sabella and Redish, 2007). The student who has failed to understand may lack additional knowledge related to the activation of, and relationships between, concepts, that may be difficult to express in words.

Finally, understanding has been linked with ability to transfer learning across a range of situations, including to novel contexts (de Regt, 2004). Therefore, a common approach to assessing understanding, often used in formal examinations, is to examine the contexts in which students can and cannot apply their learning. It has been reported that novice learners' concepts can become 'situated' in the context in which they were learned and they may struggle to activate concepts in the same range of contexts as experts (Lave and Wenger, 1991). A learner may come to appreciate the adaptations of mammals but fail to realise that plants or microbes are also adapted to their environments. One aspect of this skill is becoming fluent at translating information between the different forms of representation that are used by scientists, for example, being able to present the same information as a graph, table or diagram (Tytler, Prain and Hubber, 2013).

The models of understanding examined suggest that, in addition to acquiring the target knowledge, students should be supported to:

- appreciate the relationships between concepts;
- develop mental models;
- develop an appreciation of cause and effect and appropriate tacit knowledge;
- transfer concepts acquired in one context to other contexts and convert information between different types of representations.

Strategies to support learners

Supporting students to acquire scientific concepts is an important part of the role of the science teacher but might be thought of as only the first phase of the learning process. Once a student possesses many of the desired concepts in a topic, the second phase of learning, which focuses on the appropriate activation and relation of concepts, can begin. The second phase requires different teaching approaches from those used in the first phase to introduce new concepts. Some strategies to support learning in the second phase are described below.

Seeing the bigger picture

Understanding can be conceptualised as the ability to perceive the relationships between concepts (Kvanvig, 2003). An appreciation of the connections between concepts is an important goal in some models of learning, for example, in the Structure of Observed Learning Outcomes (SOLO) taxonomy (Biggs and Collis, 1982). However, students learning science can acquire many of pieces of knowledge, yet fail to appreciate how those elements relate together, a fragmentation learning impediment (Taber, 2005). Some learners may be only weakly aware that the concepts they are taught are part of a network of relationships and have little expectation that the concepts learned in one topic relate to those acquired in another (for example, to a student, the concept of energy may appear to have distinct manifestations in the different sciences). Without assistance, students may develop fragmented conceptual structures, consisting of isolated pieces of knowledge. Some strategies to assist students to perceive the relationships between concepts are described below.

Use concept maps to support students' appreciation of the relationships between concepts

Concept maps are commonly used to assess learning in science classrooms but they can also be used to highlight conceptual relationships. Learners can gain insight into the conceptual structure of a topic by creating a concept map, comparing their representation with those of experts, and noting differences in the manner in which the relationships between concepts are constructed. Alternatively, concept maps can be used to show learners how a concept fits in to a wider network of ideas. A teacher might begin or end a lesson by displaying a concept map that highlights how the novel concepts taught in that lesson relate to the wider conceptual structure of the topic.

Set questions that encourage students to make links between concepts

When teaching a new concept, teachers may deliberately set students problems that focus on the activation of that concept in isolation from other knowledge. This is a sensible strategy during the first phase of conceptual acquisition as it reduces the cognitive load on a learner. However, if students do not encounter problems that require them to relate several concepts in an explanation, they may develop a fragmented and poorly connected conceptual structure. Once learners are confident at applying a concept on its own, opportunities could be provided that encourage the formation of links to other concepts. For example, when initially learning about photosynthesis, questions may focus simply on activating knowledge closely related to the process, for example recalling the formula and making predictions about the behaviour of plants in different conditions. Once the base knowledge has been acquired, students' understanding can be supported by encouraging the formation of links to other concepts. For example, students might answer questions on the role of plankton in global warming, or the flow of energy in food chains.

Developing mental models

Provide opportunities for students to develop, use and critique mental models

Once students have some familiarity with the concepts in a domain, they can be encouraged to develop mental models that allow them to predict the behaviour of a system. For example, after teaching and checking knowledge about the particle model of gases, a teacher might introduce the idea that expert scientists often develop mental models of situations and describe their own mental model of the particles in a gas. The students might then be asked to make predictions in a number of contexts, for example: 'What happens to the pressure in a balloon when its volume is reduced?' If students are asked to make predictions in a range of contexts, a discussion of where their models work well, and where they break down, can provoke an analysis and refinement of their mental simulations. The focus of the activity then is not on the acquisition of more knowledge but on honing the manner in which concepts are related and triggered to make successful predictions.

Supporting knowledge of causality and awareness of tacit knowledge

Highlight cause and effect relationships

Learning about science often requires students to have an appreciation of causal relationships. Novice learners, however, often assume that there is a simple one-to-one correspondence between cause and effect (Grotzer, 2012), for example, the brightness of a bulb is assumed to depend only on the magnitude of the current flowing through it. In many contexts taught in school science, more complex networks of causal relationships exist and explicitly highlighting the nature of such mechanisms may support the development of students' understanding. In the context of direct current electrical circuits, a teacher might explicitly discuss different types of cause and effect relationships and highlight the non-sequential causality of a circuit (i.e. changing one component doesn't just affect components that are 'downstream' of it, but may cause changes across the circuit).

Make tacit assumptions explicit

Novice learners may develop beliefs about the world without an explicit awareness of the origins of their intuitions. For example, they may give answers that imply that a resultant force acts on objects travelling with constant velocity without an explicit awareness that they are applying this model of motion. The tenacious nature of such intuitive beliefs means that simply informing students about scientific models is often ineffective in causing their ideas to change, but some evidence suggests that providing opportunities for the explicit discussion of students' tacit knowledge may help to support understanding (Hammer and Elby, 2003). For example, after introducing Newton's First Law, a teacher could inform their students that they will carry out an activity in which the focus is on developing the ability to observe and critique their own thinking, rather than acquiring new knowledge. First, students' intuitions about force and motion might be elicited by demonstrating the motion of a slider on an air-track and asking them to describe the forces that act. The teacher might explain that learners often have the intuition that a resultant force acts on an object moving at constant velocity and introduce students to the skill of monitoring their thinking to notice when they activate intuitive beliefs and when they activate scientific knowledge. It should be acknowledged that this is a difficult skill to learn. The students can be given a set of questions about forces and motion in a range of contexts and be asked to reflect on which situations activate their tacit knowledge and which their scientific knowledge of force.

Encouraging the appropriate contextual triggering of concepts

Science teachers face a dilemma when teaching the theoretical concepts that are part of science curricula. Grounding an abstract idea, such as Newton's First Law, in a concrete and familiar context, such as the motion of an ice hockey puck, can help students to make sense of a challenging abstraction. However, it has been observed that students' learning may become situated (Lave and Wenger, 1991), that is, tied to a particular context, and learners may struggle to transfer concepts to different situations. Students who have learned about Newton's First Law in the context of ice hockey may not activate the knowledge when considering an object in deep space – superficially the situations appear to be unrelated. Some strategies to assist learners to transfer learning to appropriate contexts are listed below.

Introduce a new concept with a range of examples and an explicit discussion of the contexts to which the concept is applicable

It is challenging for students to independently assess the salient features of the example used to introduce a concept and it will assist students' ability to transfer if the choice of exemplar is discussed. For example, adaptation is often introduced by discussing characteristics of animals, which may lead to a narrow understanding of the concept. A discussion of examples of adaptations of plants or bacteria may help to broaden students' understanding. Moreover, a teacher might explicitly state that evidence of adaptation is observed in all organisms.

Model the ability to go beyond the 'surface features' of contexts

Researchers have reported that novices categorise situations differently from experts (Chi, Feltovich and Glaser, 1981). For example, while an experienced physicist might perceive problems about the motion of a block down a slope and the compression of a spring as similar, because they share a 'deep structure' related to energy conservation, a novice might focus on the 'surface features' of the problems (for example, one contains a spring, the other a slope) and perceive the contexts as distinct cases. A useful activity may be to produce a set of cards illustrating a range of contexts and ask students to sort them into groups with shared 'deep structures'. The teacher can then describe their interpretation of similar cases and the students can be asked to add additional contexts to those in the set.

Set a range of types of problems

When learners first learn a new concept or skill, it can be useful for them to attempt a number of problems that are similar to a worked example demonstrated by their teacher, for example when first carrying out distance, speed and time calculations. However, if students only encounter problems situated in a narrow range of contexts, or that require the formulaic application of knowledge, they may struggle to transfer their learning to other situations. A learner who has only encountered speed calculations in the context of macroscopic vehicles may not, automatically, assume that the same formula can be applied to the motion of particles or galaxies. Moreover, if students only encounter problems that require the repeated application of a set of procedures introduced by their teacher, they may develop a narrow view of the nature of scientific problem solving. It would be beneficial if students sometimes encountered problems that required them to break from previously learned procedures and to develop novel solution approaches (Brock, 2015).

Support representational fluency

A particular challenge for students learning science is that they will encounter the same information represented in different forms (Tytler *et al*., 2013). For example, students will be expected to understand the relationship between a force diagram and a photograph of a situation. Science teachers make use of representations at different scales and expect students to appreciate that the same entity is being represented. For example, water may be represented at the macroscopic level by a drawing of a beaker of water, at the submicroscopic level by a diagram of water molecules, and at the symbolic level by the H_2O notation. Translating between these representations is challenging and students should be given opportunities to practise transferring information between formats. For example, a teacher might ask students to represent a situation in which a number of forces act in equilibrium, such as a balanced seesaw, as a sketch, a force diagram, a table of data, and a series of equations. In addition, the assumptions adopted in representations may not be made explicit. For example, the scale used to illustrate spacing between molecules in a representation of a liquid may differ from the scale used to represent the dimensions of the particles. It is therefore helpful if teachers, when using a representation, highlight the assumptions implicit in it.

Knowledge is just the start

Acquiring knowledge about scientific concepts is a necessary part of learning about science. However, knowledge acquisition is only the first phase of learning which must be completed before students can being the second phase, learning how to relate and apply the acquired knowledge in the same way as expert scientists. It may be helpful for teachers to distinguish between these two phases, by highlighting the phases' differing learning aims to students and selecting activities that match those goals. Lessons, or parts of lessons, that focus on knowledge acquisition might include repeated opportunities to practise newly acquired concepts in a narrow range of contexts and introduce strategies for retaining knowledge. In the second phase, teachers should emphasise that knowing all the facts is only the first part of successful learning and describe the aspects of understanding outlined above. A lesson, or part of a lesson, focused on supporting understanding might begin with an audit of students' knowledge, and any conceptual gaps that could impede understanding should be addressed. The teacher should inform their students that the activities they will complete do not require them to gain new knowledge and that the aim of the work is to develop their ability to activate and relate concepts. Students can then be given a set of questions situated in a wide range of contexts that draw on their existing knowledge and encourage the formation of links between concepts. Once the students have attempted the problems, a scaffolded discussion of their answers could take place. This discussion might be imagined as a process of 'debugging' during which students identify 'learning bugs' (Taber, 2005: 219) in their responses. The teacher might ask the students to identify evidence of the following 'bugs':

- I failed to link some concepts or linked concepts inappropriately.
- My mental model led to an incorrect prediction in this case.
- I mistakenly categorised a cause or effect.
- Some tacit knowledge caused my incorrect response.
- I activated appropriate knowledge in some contexts but in not others.

The activity could conclude with students writing a list of strategies to avoid identified 'learning bugs' when encountering problems in the future, for example: 'Be alert to the force linked to motion belief' or 'I make mistakes balancing equations when the same element is in more than one compound'. The teacher could support students by verbalising their thought processes when solving the problems, for example by highlighting links they notice to similar contexts or modelling the suppression of tacit knowledge. The pressures created by the need to deliver knowledge-rich curricula in limited teaching time may mean that science teachers struggle to complete the knowledge acquisition phase of learning and have limited opportunities to develop their students' understanding. It is hoped that the strategies presented in this article will encourage teachers to find time to focus on the significant second phase of learning during which students develop understanding.

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Richard Brock taught secondary physics before completing his PhD in science education. He is currently a Postdoctoral Fellow in Science Education at King's College London.
Email: richard.brock@kcl.ac.uk