Diagnostic assessment in science as a means to improving teaching, learning and retention

David F. Treagust, Science and Mathematics Education Centre, Curtin University of Technology, Australia
D.F.Treagust@curtin.edu.au

Introduction

The nature and extent of students' understanding of scientific concepts and phenomena are key components of any science curriculum. In order to gauge the effectiveness of classroom instruction to facilitate students' understanding of scientific concepts, appropriate assessment tools have to be readily available for use by classroom teachers. This paper addresses the importance of assessment in science learning and presents a review of the development, in particular, of two-tier multiple-choice diagnostic instruments that have been reported in the science education research literature and suggests that their development and use can make an important contribution to improving teaching, students' learning and maintaining student interest in the science concepts with which they are engaged.

Students' alternative conceptions and the importance of diagnostic assessment

Research data collected over more than three decades has shown that the majority of students come to science classes with pre-instructional knowledge or beliefs about the phenomena and concepts to be taught and many students develop only a limited understanding of science concepts following instruction (Duit and Treagust 2003). These students construct sensible and coherent understandings of phenomena and concepts as seen through their own eyes that do not match the views that are universally accepted by the scientific community. The resulting misunderstandings or alternative conceptions, if not challenged, become integrated into students' cognitive structures and interfere with subsequent learning. As a consequence, students will experience difficulty in integrating any new information within their cognitive structures, resulting in an inappropriate understanding of the new concept.

The large body of research literature on students' understanding of science concepts and how researchers have attempted to provide interventions has been categorised, synthesised and summarised by Duit (2004) in a manner that enables researchers to gain a holistic understanding of the field. Other research shows that the majority of teachers do not effectively diagnose students' learning problems, especially at an early stage of the student learning process (see for example, Costa, Marques and Kempa 2000; Taber 2001).

Consequently, of equal interest is how teachers can address students' learning needs by incorporating in their instructional repertoires specially designed assessment procedures that are consistent with constructivist teaching approaches and are an integral part of that teaching (see for example, Bell 2000; Black 1999; Treagust, Jacobwitz, Gallagher and Parker 2001). Wiggins and McTigue (1998) recommend redesigning the curriculum in a way that includes informal and formal assessment procedures for understanding as part of the curriculum. These authors recommend that teachers use a wide range of both formative and summative assessment methods to gain feedback on student learning. The difficulty with most effective methods is that they are very time consuming and rarely practical for busy classroom teachers to create.

Reforms in assessment

Over the past decade, science education reforms in Australia (Curriculum Corporation 1994), the United States of America (National Research Council 1996), England (Department of Education and Employment 1995), and Canada (Council of Ministers of Education, Canada 1997) as well as in other countries, indicate an increasing awareness that the science curriculum offered in schools is not meeting the needs of society today and is likely to be inadequate for the future.

One component of this reform concerns making judgements about students' performance as they learn scientific concepts in the curriculum that are much more complex than initially might appear (see for example, Duit and Treagust 2003). In most of these reports about curriculum reform, the concerns about assessment, examinations and testing are usually presented as refinements of existing technical testing procedures. Nevertheless, there have been notable changes from the norm of testing procedures. For example, in several instances, items are being used that assess broad scientific understanding, referred to as scientific literacy, rather than essential scientific facts (see for example, the items in the OECD Programme for the International Student Assessment (2001). However, the items in these latter tests are used in a summative manner, and are not designed to provide teachers and students with feedback about students' learning of the concepts being investigated.

Many researchers recommend that alternative forms of assessment are needed that might permit the assessment of thinking rather than the possession of information and that this assessment should be an integral part of teaching (Bell 2002; Bell and Cowie 2001; Black 1999; Wiggins and McTighe 1998; Wolf, Bixby, Glenn and Gardner 1991). These alternative assessment procedures are presented in a context of learning and include a wide range of possibilities from performance tasks and portfolio-like components. For example, assessments by performance tasks require students to write, read, and solve problems in genuine rather than artificial ways. How teachers use these tests as an integral part of their teaching is described as planned formative assessment (Bell 2000).

In order for science teachers' pedagogy to be more effective, diagnostic formative assessment methods are needed because research suggests that current assessment procedures distort and narrow instruction, misrepresent the nature of the subject, and underscore inequities in access to education (Wolf et al. 1991). Furthermore, current assessment procedures are claimed to not provide valid measures of what students know and to provide no opportunity for students and teachers to be involved in discussions about the work being assessed (see for example, Black and Wiliam, 1998). Wolf et al. (1991) claim that a change in this direction of in-class formative assessment "might enable teachers to develop sophisticated clinical judgements about students' understanding of significant ideas and processes and encourage educators to discuss, rather than simply measure, educational progress" (p. 33). One such successful approach is embedded assessment where the teachers are able to incorporate a wide variety of formative assessment procedures within their teaching (see Treagust et al. 2001). These alternative forms of assessment are different to those generally used by science teachers in that standard tests are largely paper-and-pencil collections of individual items with single correct answers presented without a surrounding context.

A change in direction from those assessment procedures generally used by teachers is highly recommended by many authors and is used in the Programme for International Student Assessment (OECD/PISA 2001) initiated by the Organisation for Economic Cooperation and Development. However, as already stated, the recommendations and outcomes are without the diagnostic formative assessment approaches suggested above. To bring these approaches to fruition by science teachers, a considerable amount of inservice education for teachers about the use of alternative forms of assessment will be needed.

Supporters of alternative approaches to assessment have not specifically elaborated on the value of specially created diagnostic tests but have recommended assessment items that "require an explanation or defence of the answer, given the methods used" (see Wiggins and McTighe 1998, p. 14) – precisely the outcome of two-tier test items. Many of the concerns about testing described above can be addressed by teachers using two-tier multiple-choice assessment items that are thoroughly grounded in recent research findings in science education. The basis for this type of assessment argues that teachers must consider the intuitive knowledge base that students have already constructed if they want to understand students' thinking of science concepts and relate their teaching to this student knowledge.

Development and use of two-tier multiple-choice test items

Tamir (1989) found the use of justifications when answering multiple-choice test items to be a sensitive and effective way of assessing meaningful learning among students and addresses, to some extent, the limitations of traditional multiple-choice test items. As a result, he proposed the use of multiple-choice test items that included responses with known student alternative conceptions, and that also required students to justify their choice of option by giving a reason (Tamir 1971).

The positive outcomes of findings related to students' justifications to test items led to the development of two-tier multiple-choice test items specifically for the purpose of identifying students' alternative conceptions in limited and clearly defined content areas. These are short paper and pencil tests that are convenient to administer and not time consuming to mark. The means whereby two-tier items have been designed has been well documented by Treagust and other researchers who have implemented the approach. In brief, there are three major aspects to developing these items: (a) the content is defined by the identification of propositional content knowledge statements of the topic to be taught and the development of a concept map that accommodates the propositional statements; (b) information about students' conceptions is obtained from the extant research literature, where available, and where not available by having students provide free response explanations to their answers and conducting unstructured interviews with students who have previously been taught the content/concepts; and (c) the development of the two-tier multiple-choice diagnostic items.

The first tier of each multiple-choice item consists of a content question having usually two to four choices. The second tier of each item contains a set of usually four possible reasons for the answer give to the first part. The reasons consist of the designated correct answer, together with identified students' conceptions and/or misconceptions. The reasons are from the students' responses given to each open response question as well as information gathered from the interviews and the literature. When more than one alternative conception is given, these are included as separate alternative reason responses. Students' answers to each item are considered to be correct only if both the correct choice and correct reason are given. Finally, a specification grid is designed to ensure that the diagnostic instrument fairly covers the propositional knowledge statements and the concepts on the concept map underlying the topic. The need to select a justification in these multiple-choice items affords a sensitive and effective way of assessing meaningful learning among students and also serves as an effective diagnostic tool (Tamir 1989).

A wide range of specially created two-tier multiple-choice instruments (Treagust 1988, 1995) have been developed and used to determine students' understanding of the concepts in several science disciplines. The design and development of these items is described in the next section. An example of an item for use with 14-16 year olds studying chemical bonding is as follows (Tan and Treagust 1999). It should be noted that at this level of learning, the first tier response is relatively easy but the second tier probes deeply an understanding behind the first tier response.

The compound formed between magnesium and oxygen can be used as a heat-resistant material to line the walls of furnaces.

I True	II False
Reason	
A.	The lattice of magnesium oxide resembles that of silicon.
B.	The covalent bonds between magnesium and oxygen atoms are strong
C.	The intermolecular forces between the magnesium oxide molecules are weak
D.	There are strong ionic forces between magnesium and oxide ions in the lattice

The process of construction of two-tier multiple-choice items that test higher level abilities than recall is considered long and difficult. Examples of instruments used to investigate topics in biology, in chemistry and in physics are summarised in Table 1. These two-tier multiple-choice tests are more readily administered and scored than the other methods of ascertaining students' understanding, and thus are particularly useful for classroom teachers enabling them to use the findings of research to inform their teaching. Two-tier test items has been used by the National Science Council in Taiwan as the central part of their national assessment project and the American Chemical Society as recommended examples for conceptual questions (http://JchemEd.wisc.edu/JCEWWW/Features/CqandChP/ExTypesConceptQuestions.htm1#Tieredquestion).

Table 1. Summary of the development of diagnostic instruments since the 1980s

Topic/concept	Authors
Photosynthesis and respiration	Haslam and Treagust (1987)
Photosynthesis	Griffard and Wandersee (2001)
Diffusion and osmosis	Odom and Barrow (1995)
Breathing and respiration	Mann and Treagust (1998)
Internal transport in plants and human circulatory system	Wang (2004)
Flowering plant growth and development	Lin (2004)
Covalent bonding	Birk and Kurtz (1999)
Covalent bonding and structure	Peterson, Treagust and Garnett (1989)
Chemical bonding	Tan and Treagust (1999)
Qualitative analysis	Tan, Treagust, Goh and Chia (2002)
Chemical equilibrium	Tyson, Treagust and Bucat (1999)
Multiple representation in chemical reactions	Chandrasegaran, Treagust &. Mocerino (2005)
Ionisation energies of elements	Tan, Taber, Goh and Chia (2005)
Acids and bases	Chiu (2001, 2002)
States of matter	Chiu, Chiu and Ho (2002)
Light and its properties	Fetherstonhaugh and Treagust (1992)
Formation of images by a plane mirror	Chen, Lin and Lin (2002)
Forces	Halloun and Hestenes (1985) Hestenes, Wells and Schwackhamer (1992)
Electromagnetism	Paulus and Treagust (1991)
Electrical circuits	Millar and Hames (2001)
Force, heat , light and electricity	Franklin (1992)

Identification of alternative conceptions held by students

The administration of two-tier diagnostic instruments by researchers and subsequent analyses of the responses has resulted in the identification of several alternative conceptions that are held by students in various science topics. The 'Qualitative Analysis Diagnostic Instrument' (QADI) consisting of 19 items, for example, was administered to 915 Year 10 students after they had been taught the theory associated with inorganic qualitative analysis (Tan, Treagust, Goh and Chia 2002). The topics that were taught included acids, bases and salts, oxidation and reduction, periodicity, and reactivity of metals. The students had also been involved in a minimum of 10 qualitative analysis practical sessions. Analysis of the students' responses in the diagnostic instrument revealed that 18 alternative conceptions were held by at least 10% of the sample. Several of these alternative conceptions are summarised in Table 2.

Table 2. Several alternative conceptions determined from administration of the QADI to Year 10 students (N = 915)

Alternative conceptions	Percentage of students with alternative conceptions
Displacement	
A more reactive ion displaces a less reactive ion in a double decomposition / precipitation mixture.	25
Redox	
A redox reaction occurs in a double decomposition reaction involving the use of alkalis.	13
Dissolution	
A precipitate is formed when a reagent is added to an unknown solution. On further addition of excess reagent, the precipitate disappears. More excess reagent means more space/volume for the precipitate to dissolve.	29
Heating solid substances	
All gases have to be tested when a substance is heated.	23
Ionic compounds have strong bonds and do not decompose on heating	26

One item involved the chemical reaction that occurred when aqueous ammonia was added to aqueous copper(II) sulfate. About 13% of the students may have deduced that oxidation and reduction had occurred because ammonia had gained oxygen to produce ammonium sulfate. At the same time, copper(II) sulfate was thought to have been reduced to copper(II) hydroxide due to a loss of oxygen. These students appear to have used the inappropriate oxygen model for redox reactions (Garnett and Treagust 1992).

In an example taken from biology, Lin (2004) designed a 13-item two-tier multiple-choice instrument, the "Flowering Plant Growth and Development Diagnostic Test". The test was administered to 156 students from Year 10 and 321 students from Year 11 (161 science majors and 160 non-science majors). To illustrate the extent of the findings in this study, Lin identified 14 alternative conceptions that were held by at least 10% of the 161 science majors in Year 11. Several of these alternative conceptions are listed in Table 3.

The belief that solar energy is directly utilised for cellular activity suggests that the students probably did not possess basic understanding of the processes of photosynthesis and respiration in plants. This as well as other alternative conceptions that have been identified provide useful indicators for the planning of classroom instruction.

Conclusion and implications for pedagogical practice

Reforms in science education generally place greater emphasis on the content of curricula than on new assessment procedures. The use of two-tier diagnostic tests discussed in this paper can help to address many of the concerns about current assessment practices by overtly assessing the outcomes of thinking within a specified context rather than assessing knowledge of information.

Table 3. Several alternative conceptions determined from administration of the Flowering Plant Growth and Development Diagnostic Test to Year 11 students (N = 161)

Alternative conceptions	Percentage of students with alternative conceptions
Seed germination	
Seeds need water during photosynthesis to produce nutrients for germination.	23
Seeds do not need oxygen for germination because seeds themselves provide energy for germination.	13
The organic matters in soil are used as nutrition for seed germination.	27
Plant nutrition	
Plants transfer solar energy directly into energy for cellular activity.	16
Mechanism of growth and development	
Roots turn and grow into the ground for getting more food.	16
Temperature control will make plants change the time to produce florigen and adjust flowering.	18

By using these diagnostic instruments at the beginning or on completion of a specified topic, science instructors can achieve better understanding about the nature of students' understanding and the existence of any alternative conceptions or misconceptions in a particular topic being studied. Once students' alternative conceptions are identified, science instruction can be modified to remedy the problem by developing and/or utilising alternative teaching approaches that specifically address students' non-scientifically acceptable conceptions. In the diagnostic instrument on qualitative analysis, for example, it was found that students had difficulty grappling with the concepts of oxidation and reduction; at least three models of redox reactions are commonly encountered in a chemistry course Garnett and Treagust 1992). Science instructors need, therefore, to pay more attention to clarifying these models during instruction so that students will be in a position to confidently use them to decide if a chemical reaction is a redox reaction.

The students' conceptions that can be identified using these two-tier diagnostic instruments are often well known to experienced teachers, but are appreciated by less experienced teachers only after instruction has been completed. In the latter instance, there is no possibility to consider students' conceptions of the phenomena and to incorporate these in the teaching process. Research evidence also suggests that experienced teachers frequently do not appreciate the problems encountered by students in learning complex science concepts. There are two reasons for this. First, regular approaches to instruction do not probe sufficiently for reasoning of answers. Second, the usual assessment procedures do not demand such detailed explanations of concepts. However, the use of these diagnostic instruments and subsequent change in teaching emphasis does not guarantee that alternative conceptions will not be constructed and retained by students.

It is of great concern in several countries that there is continuing low participation rate of students taking science in higher levels of secondary school education, including among Years 11 and 12

students in Australia. In particular, enrolments are on the decline in the more conceptually demanding calculus-based options that lead to acceptance in university science and engineering courses (Dobson 2003; Hassan and Treagust 2003). There are even more dramatic enrolment declines in other countries such as Great Britain and France (Nature 2002). Indeed, the success, and even the continuation, of science programs at university are dependent on foundational improvements in science education in secondary schools.

One way to encourage more students to study science is by presenting science to them in such a way that, through the teachers' planned formative assessment using multiple-choice diagnostic items, students can begin to question and understand the underlying science concepts. Through this teaching, students will be encouraged to think about the concepts and consider alternative explanations rather than memorise basic facts for a test or examination which are then forgotten.

The use of these diagnostic instruments in classroom instruction as a means of planned formative assessment will also enable teachers to diagnose students' conceptions in particular areas as well as serve as a means of remediation prior to any summative assessment. Through cooperative group work as well as a variety of individual learning opportunities, teachers can help students examine their own understanding. When used effectively, these tests can contribute to students' deeper understanding of the science concepts in the curriculum.

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Appendix 1

Published and available two-tier tests in science content areas

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