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Development and use of diagnostic tests to evaluate students' misconceptions in science

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There is now a large body of research which examines students' misconceptions in a variety of science subject areas. A problem exists, however, in applying the findings of this research to the classroom. One means of improving the application of misconceptions research is by the use of diagnostic tests which incorporate the findings of this research. A methodology for developing these diagnostic tests and the use of two such tests—in chemistry (covalent bonding and structure) and in biology (photosynthesis and respiration in plants)—are described. Analysis of the results of the tests given to class groups illustrate the ease of identification of misconceptions which can be subsequently addressed by the teacher.

Introduction

In recent years students' understanding of scientific phenomena have been of considerable interest to science education researchers, cognitive psychologists and teachers of science. It is now generally agreed that students bring with them to science lessons certain ideas and notions that are well established in their ways of thinking but are inconsistent with the ideas of teachers and scientists. Students' conceptions which are different from those generally accepted by the scientific community have been called 'misconceptions' (Helm 1980), 'preconceptions' (Novak 1977), 'alternative frameworks' (Driver 1981) or 'children's science' (Gilbert et al. 1982). There is currently a large body of this research in the literature which has been summarized in articles by Driver and Erickson (1983) and Gilbert and Watts (1983) and in a monograph by Pfundt and Duit (1986).

Following on from the approach to probing children's thinking developed by Piaget, the usual means for obtaining information about students' misconceptions has been through individual student interviews. Osborne and Gilbert (1980) and Watts (1981) have described a variety of interview formats or procedures for conducting these interviews. The two most commonly used procedures by researchers are interviews about instances and interviews about events. Some researchers such as Mitchell and Gunstone (1984) have used an interview format which is a mixture of these procedures.

Exceptions to this line of research have been multiple choice tests described by several authors such as Tamir (1971), Linke and Venz (1978 and 1979), Helm (1980), Trembath (1984) and more recently by Halloun and Hestenes (1985). In the case of Tamir (1971) and Linke and Venz (1978,
1979) the tests were related to specified and limited content structure. The multiple choice tests by Helm covered a semester's work in college physics while that of Trembath covered a wide range of subject content areas in a variety of disciplines at the college level.

The work by Tamir (1971) on an alternative approach to construction of multiple choice test items was innovative in that the distractors for the multiple choice items were based on students' answers to essay questions and other open-ended questions and addressed underlying conceptual knowledge related to a limited content area. As Tamir (1971, p. 306) states 'These alternative [responses] being representative of typical conceptions and misconceptions of students have a distinctive advantage as compared to regular test items for which professional test writers provide the alternatives.' To the best of this author's knowledge, Tamir's approach has not been pursued further as interest in students' misconceptions has expanded though authors such as Simpson and Arnold (1982, p. 181) recommend that information 'relating to peculiar and erroneous information held to be true by pupils' should be included in tests which depart from the usual norm-referenced paradigm.

In their multiple choice items, Linke and Venz (1978) examined the principles of structure of matter, changes of state and solubility and the basic principles of electricity. In their later study, Linke and Venz (1979) examined students' misconceptions of the radiation of light and heat, chemical reactions and motion and forces. The items, which contained distractors based on students' identified misconceptions from parallel free response items, were administered to non-science secondary students in years 11 and 12 (aged 16-18); the general conclusion was that students completing secondary studies hold identifiable misconceptions or confused ideas.

In order to objectively evaluate first year college physics instruction, Halloun and Hestenes (1985) developed a physics diagnostic test which assessed students' basic knowledge of mechanics. The items were initially selected to assess the students' qualitative conceptions of motion and its causes and to identify common misconceptions already noted by previous investigators. Item distractors were chosen from students' responses identified as misconceptions on earlier tests.

The development of multiple choice tests on students' misconceptions has the potential to make a valuable contribution, not only to the body of work in the area of misconceptions, but also to assist in the process of helping science teachers use the findings of research in this area. It is well documented that research findings in science education take considerable time to be applied in the classroom and the development of tests incorporating research findings, which can be readily utilized by classroom science teachers for their own purposes, would appear to be one way of improving the rate of this application. The alternative of teachers interviewing their own students to identify misconceptions is fraught with problems since not only is interviewing time consuming, it also requires substantial training (Fensham et al. 1981).

One way for a classroom teacher to more easily identify misconceptions held by a group of students would be to administer a pencil and paper
multiple choice test which has items specifically designed to identify misconceptions and misunderstandings in a limited and clearly defined content area. Such a test could be used as a diagnostic tool and help the teacher to begin to address existing misconceptions based on earlier teaching and learning prior to commencing the topic or which have occurred following teaching of the topic. It is, however, well documented that the task of changing misconceptions will not be easy since misconceptions have often been incorporated securely into cognitive structure (see for example, Ausubel 1968, Driver and Easley 1978, Gunstone et al. 1981). Nevertheless, a teacher needs a starting place for addressing known misconceptions and a multiple choice diagnostic test would appear to provide a relatively straightforward method. This paper describes a methodology and its subsequent use for developing diagnostic tests to examine and identify students’ misconceptions in limited content areas of science. To date, this methodology has been used to develop two diagnostic tests; one on covalent bonding, a grade 11 and 12 chemistry topic (Peterson 1986) and a second on photosynthesis and respiration, a biology topic taught in both lower and upper high school (Haslam 1987).

**Research methodology**

Broadly, the development of the diagnostic tests for identifying students’ misconceptions in specific content areas comprises ten stages involving three broad areas. The essential features of much of the current misconception/alternative framework research methodology involving interviews and free responses to pencil and paper tests are included as steps 6 and 7.

**Defining the content**

The first four steps are concerned with defining the concept boundaries and involve the identification of propositional content knowledge statements and the development of a concept map. The first two steps and their inter-relationship are usually developed at the same time in a similar manner to that described by Stewart (1980).

**Step 1: Identifying propositional knowledge statements.** The importance of identifying propositional knowledge statements has been described by Finley and Stewart (1982) who further outlined the advantages of this approach in curriculum development and teaching. Using this technique 33 propositional knowledge statements were identified for the covalent bonding topic, while 34 and 21 statements, respectively, were identified for photosynthesis and respiration in plants.

**Step 2: Developing a concept map.** A map of concepts which relate to the topic under investigation was developed based on the procedure described by Novak (1980). As with the development of propositional knowledge, this activity enables the researcher to carefully consider the nature of the content which has been selected for instruction.
Step 3: Relating propositional knowledge to the concept map. The propositional knowledge statements are related directly to the concept map to ensure that the content being examined is internally consistent. This is a reliability check that the underlying concepts and propositional statements are indeed examining the same topic area. To ensure that the concept area is properly documented it is essential that there is a representative covering of concepts and propositional statements for each topic under investigation.

Step 4: Validating the content. The propositional statements and the concept map are content validated by science educators, secondary science teachers and science specialists with a thorough knowledge of the subject matter. Any discrepancies or irregularities are removed and the list of propositional statements and the concept maps are corrected and modified. In this way the knowledge being examined is thoroughly documented so that no questions are developed for the multiple choice test which do not relate clearly to the concepts being taught. An essential feature of this development is that the content and concepts to be investigated are scientifically accurate as far as the particular level of study being pursued. The final revised list of propositions and the concept map reflect the input from persons with considerable knowledge in these content areas.

Obtaining information about students' misconceptions

The second broad area for developing diagnostic tests to evaluate students' misconceptions involves a thorough examination of the relevant literature dealing with cognitive structure and conceptual change, interviews with students about their understanding of the science content and obtaining responses from open ended pencil and paper questions.

Step 5: Examining related literature. Before commencing new efforts to identify problems and/or misconceptions in the subject area under investigation, it is essential to examine the related literature dealing with research on misconceptions. For the work on covalent bonding a review of the literature did not identify any research on misconceptions being conducted on this topic. On the other hand, there has been considerable research concerning students' misconceptions of the topics of photosynthesis and respiration in plants. Examples of recent work are those reported by Bell and Brook (1984), Roth et al. (1983) and by Wandersee (1983). By examining the descriptions of students' misconceptions and those areas with conceptual difficulty it is possible to begin to build up a base of information for developing multiple choice questions on misconceptions.

Step 6: Conducting unstructured student interviews. In order to gain a broad perspective of students' understanding of both topics, unstructured tape recorded interviews took place with students who had recently completed the topics. These discussions help to identify any areas of misunderstanding and/or misconceptions and give rise to the development of ideas for further probes by multiple choice questions with a free response. The discussion related to open ended questions such as 'What is a covalent bond?', 'Why do
molecules have different shapes?’, ‘How does a plant obtain food?’ or ‘Explain what happens when plants respire’. Students’ responses were probed further and any misconceptions or differences in thinking compared to the teacher were identified. This part of the methodology could easily be conducted with interviews about events or interviews about instances cards but in this case a more open ended approach was taken.

Step 7: Developing multiple choice content items with free response. Items of a multiple choice nature are written based on the topic being taught. Each item is based on a limited number of propositional statements and is designed to address misconceptions encountered in the literature and the interviews. Each multiple choice item is followed by a space for the student to complete the reason why the particular option of the multiple choice was selected. After a series of items have been developed which are representative of the topic, a test is given to a class of students. Further misconceptions as well as acceptable scientific conceptions become further evident in the free response answers. This technique is in common use and has been described in much detail by Driver (1984) and her co-workers and earlier by Osborne (1980) and his co-workers.

Developing a diagnostic test

The third broad area for the test construction involves the development of two tier test items, of which the first tier requires a content response and the second tier requires a reason for the response.

Step 8: Developing the two tier diagnostic tests. A two tier diagnostic test is developed from the multiple choice items with a design comparable to the format of the ‘Test of Logical Thinking’ (Tobin and Capie, 1981). The first part of each item on the test is a multiple choice content question having usually two or three choices. The second part of each question contains a set of four possible reasons for the answer given to the first part. The reasons consist of the correct answer, any identified misconception or misconceptions, together with a simple wrong answer if needed. This second part of each item in the test is developed from the students’ responses on the reasons given to each open response question as well as information gathered from the interviews and the literature. When more than one misconception has been given by students earlier, more than one misconception is included in the alternative reason responses. Examples of these two tier diagnostic test items and how they function are described below. Subsequently, both diagnostic tests described here contain items having two parts. The first part is the multiple choice content question. The second part of each item consists of a multiple choice set of reasons for the answer given in part one.

Step 9: Designing a specification grid. A specification grid is designed to ensure that the diagnostic test fairly covers the propositional knowledge statements and the concepts on the concept map underlying the topic.
Step 10: Continuing refinements. Successive refinements of the two tier multiple choice items with different classes ensures that the test as a whole can be used for diagnosing students’ misconceptions in the topic under examination. The development of these tests to date has shown that each item can be successfully refined to improve its diagnostic nature to identify misconceptions. In this regard, there is no short cut to obtain initial information on student responses other than a thorough review of misconceptions work already described in the literature, talking to students in interviews and collecting data from pencil and paper open-ended test items. Each administration of the test to different groups of students provides improvements in isolating the misconceptions for each item.

Using multiple choice tests to diagnose misconceptions

Based on this methodology, diagnostic tests from chemistry and biology have been developed by Peterson (1986) and Haslam (1987). The instruments, ‘Covalent Bonding and Structure’ and ‘What Do You Know About Photosynthesis and Respiration in Plants?’, are two tier item multiple choice tests containing 13 and 15 items, respectively. Aspects of the test characteristics and details of their use are to be found in Peterson et al. (1986) and in Haslam and Treagust (1987). Two items, one from each test, are presented to illustrate how the items work and how the data can be used by classroom science teachers.

The seventh item of the ‘Covalent Bonding and Structure’ diagnostic test (see figure 1) assesses students’ understanding of intermolecular forces and is based on three propositional knowledge statements, namely:

- Intermolecular forces, or weak forces of attraction, exist in varying degrees between molecules.
- Whether a substance composed of molecules exists as a solid, liquid or gas at room temperature will depend on the magnitude of the intermolecular forces between molecules.
- Molecular substances with high melting and boiling points have strong intermolecular forces between molecules.

The data are from responses of four groups of students. Groups 1 and 2 are composite grade 11 and 12 chemistry students, respectively, in South Australia. Groups 3 and 4 (aged 18–19 years) are first year tertiary chemistry students from two institutions in Western Australia. The majority of students in all groups (87%, 97%, 100% and 89%) responded correctly that intermolecular forces account for the difference in state of hydrogen sulphide and water at room temperature. Almost all these chemistry students were aware of the relationship which exists between the strength of the intermolecular forces and the melting point/boiling point of a substance. However, only 11%, 33%, 19% and 18%, respectively, correctly understood why this relationship exists. A large percentage of students (63%, 40%, 73% and 64%) selected choices 1A or 1B which relate to the strength of intramolecular bonds. These students appear to be making a consistent error and the misconception is easily identified by the teacher using this item. Indeed, the major misconception being addressed, which was earlier
Water (H₂O) and hydrogen sulphide (H₂S) have similar chemical formulae and have V-shaped structures. At room temperature, water is a liquid and hydrogen sulphide a gas. The difference in state between water and hydrogen sulphide is due to the presence of strong intermolecular forces between

(1) H₂O molecules (2) H₂S molecules

Reason

(a) The difference in strength of the intermolecular forces is due to differences in the strength of the O–H and S–H covalent bonds.
(b) The bonds in H₂S are easily broken, whereas in H₂O they are not.
(c) The difference in strength of the intermolecular forces is due to the difference in polarity of the molecules.
(d) The difference in strength of the intermolecular forces is due to the fact that H₂O is a polar molecule, and H₂S is a non-polar molecule.

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*the correct choice and reason response

Figure 1. Item number 7 from the ‘Covalent Bonding and Structure’ diagnostic test showing percentage of students selecting alternative responses.

identified by interview and in the free response format, related to the common misunderstanding that ‘intermolecular forces are the forces within a molecule’. A second misconception addressed in choice B of item 7 was that ‘covalent bonds are broken when a substance changes state’. This misconception, selected by 49%, 17%, 30% and 24% of the students, respectively, indicates these students had not understood the nature of intermolecular forces compared with the forces within a molecule. This misconception is similar to that reported by Osborne and Cosgrove (1983) where students considered that the bonds in water molecules were broken when water changed state.

The second item of ‘What Do You Know About Photosynthesis and Respiration in Plants?’ test (see figure 2) investigates students’ comprehension of the gas being taken in by plants when there is no light
Which gas is taken in by green plants in large amounts, when there is no light energy at all?

(1) carbon dioxide gas
(2) oxygen gas.

The reason for my answer is because:

(a) This gas is used in photosynthesis which occurs in green plants all the time.
(b) This gas is used in photosynthesis which occurs in green plants when there is no light energy at all.
(c) This gas is used in respiration which only occurs in green plants when there is no light energy to photosynthesize.
(d) This gas is used in respiration which takes place continuously in green plants.
(e) 

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*the correct choice and reason response
—no responses in this category

Figure 2. Item number 2 from the 'What Do You Know About Photosynthesis and Respiration in Plants?' diagnostic test showing the percentage of students selecting alternative responses.

energy. Specifically this item addresses the following four propositional knowledge statements:

- All organisms, plants and animals, respire continually.
- Oxygen is taken in during respiration.
- Photosynthesis takes place only in the presence of light energy.
- Oxygen gas is given off by the green leaves (or green stems) during the process of photosynthesis.

The first two propositional knowledge statements are addressed directly by item 2 while the second two statements are addressed implicitly. The data are from responses of students in grades 8–10 in one school and from students in
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grades 11 and 12 in three schools from comparative socioeconomic areas. The results indicate that this sample of students does not have a clear understanding of the process of respiration. When the first part of the item only is taken into consideration (end column), the results show that there is generally an increasingly correct response choice from grades 8–12 (39%, 44%, 41%, 65%, 88%) about which gas is taken in in large amounts by green plants when there is no light energy at all. However, when students’ reasoning for their choice in the first part of the item is taken into consideration, the correct response is much lower (9%, 11%, 7%, 28%, 65%). While there is generally less selection of alternative reasons at each successively higher year level, it is not until grade 12 that responses indicate that this sample of students have a reasonably clear understanding of respiration in plants and even then it is less than anticipated for students at this level. These results are perhaps surprising when one realizes that respiration is taught as an identified topic in grade 8 and is addressed throughout biology units in later years of secondary school in Western Australia. Nevertheless, the results illustrate students’ misconceptions and lack of understanding that respiration in plants is an ongoing continuous process during both light and dark conditions.

Implications for teaching science

While reported research on students’ misconceptions are inherently interesting and are illustrative of students’ thinking and perhaps the failings of the implemented curricula, the results of this research are not easily used by classroom practitioners. One possible means of increasing the application of science education research into the classroom is by incorporating the findings of this research in diagnostic tests. The existence of reliable and valid pencil and paper, easy to score, test instruments will enable science teachers to better assess students’ understanding of science upon which improved teaching can be based.

By using a diagnostic test at the beginning or upon completion of a specified science topic, a science teacher can obtain clearer ideas about the nature of the students’ knowledge and misconceptions in the topic. Once misconceptions are more easily identified, a science teacher will be more inclined to remedy the problem by developing and/or utilizing alternative teaching approaches which address students’ misconceptions. For example, based on the results of the item on intermolecular forces, it is apparent that science teachers need to pay more attention to the essential meaning of intermolecular forces and intramolecular forces and to illustrate the different concepts clearly with good examples. Without this happening, it is evident that this misconception or misunderstanding will be retained as was found in groups 3 and 4 who came from a variety of high school chemistry classes. Even with this teaching emphasis, the misconception may be retained. However, by using the diagnostic test a teacher can become aware that there is a specific problem to address. Similarly, the results obtained from administering the item on respiration in plants illustrate clearly that this sample of students have a lack of understanding that this process is ongoing and continuous. By being aware of this information from their own students,
teachers can emphasize the nature of respiration at the same time as teaching about photosynthesis. Efforts to help teachers address observed misconceptions based on information from these two diagnostic tests are currently being investigated.

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