Assessing understanding in biology

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This paper discusses several new assessment strategies that encourage meaningful learning and conceptual understanding in the biological sciences. Our purpose is to introduce a handful of evaluation and measurement techniques that help students assimilate well-integrated, strongly cohesive frameworks of interrelated concepts as a way of facilitating 'real understanding' of natural phenomena. Among these methods are concept maps, V diagrams, SemNet software, image-based test items, clinical interviews, portfolios, written products, performance measures, and conceptual diagnostic tests. Evidence suggests that these methods are most useful at highlighting 'alternative conceptions' and assisting students who wish to 'learn how to learn'.
Key words: Assessment, Evaluation, Learning, Understanding.

There seems to be a growing recognition, especially among biology teachers and education researchers, of the need to refocus our classroom efforts on meaningful learning and *conceptual understanding* of scientific ideas (Mintzes *et al.*, 1997; 1998; Wandersee *et al.*, 1994). Rather than teaching and learning isolated bits of 'inert knowledge', advocates of this new view stress the need for 'quality over quantity, meaning over memorising, and understanding over awareness'. The goal is to help students assimilate well-integrated, strongly cohesive frameworks of interrelated concepts as a way of encouraging 'real understanding' of natural phenomena. Ultimately, we seek to encourage students to construct useful knowledge that is applicable in the real world, in areas such as healthcare, environmental protection, and foundational to further study in scientific disciplines for those who choose to continue such study.

The new agenda in biological education is based on some 25 years of cognitive research showing, despite the best efforts of the most creative teachers and most thoughtful scholars and curriculum designers, that the majority of students leave secondary school with a distorted view of biological objects and events (Wandersee *et al.*, 1989; Mintzes *et al.*, 1998; 2000). Further, the evidence suggests that these 'alternative conceptions' are strongly resistant to change and remain intact throughout the university years and into adult life. What can the reflective teacher do to encourage students to construct scientifically acceptable, well-integrated meanings in biology?

In this brief review article we focus on several new ways of assessing *understanding* of biological concepts as a principal route to meaningful learning (Figure 1). Our commitment to improving assessment strategies grows out of a strong conviction that the way we choose to evaluate and reward student work may be the single most significant determinant of high quality learning. In this respect we regard assessment as one of the five most important 'commonplaces' in education, along with the learner, the teacher, the curriculum, and the social milieu (Novak *et al.*, 2000).

Assessment for understanding

Biology teachers have long recognised the central role of assessment as a means of encouraging (or discouraging) meaningful learning (Hurd, 1961). The nagging feeling, now supported by substantial research evidence, is that students learn much school science by rote and retain enough of its central ideas just long enough to 'pass' a test. Furthermore, it is now clear that we ourselves are partially responsible for this state of affairs. The way we choose to assess student progress conveys much about what we value, and these values are readily discerned, internalised, and acted upon by students. The old adage, 'we get what we assess', seems as true today as ever before. If our goal is to encourage *understanding* we must make that goal clear to our students by our choice of assessment strategies. Twentieth century techniques (i.e. multiple-choice tests, fill-ins, true/false questions, and others) will not do the job.

The world of the 21st century is substantially different from the one we knew as students. What is especially clear is that we live in a strongly interconnected world, and students will need to leave school with more than just bits and pieces of disconnected knowledge. Accordingly, our revised goals must be linked, coupled, or 'aligned' with assessment techniques that encourage students to construct integrated frameworks of tightly cohesive knowledge, the kind of knowledge that can be readily accessed and used in novel, real-world settings, and built upon in successive encounters with the life sciences. Here we summarise several such techniques. Space does not permit a detailed analysis of each (for full details see Mintzes *et al.*, 2000).

When biologists and philosophers of science speak about understanding natural phenomena, they usually have some very specific criteria in mind. Among the most important criteria are:

Sharing Meanings Understanding rests on shared meanings. To understand or to be understood in a natural science requires that the meanings we assign to concept labels (eg. natural selection; mitotic cell division; chloroplast) be substantially the same or very similar to those assigned by others. In the scientific community, the accepted scientific meanings are those used by 'experts' in scholarly subdisciplines within a recognised academic field. Experts serve as arbiters in scientific disputes and the meanings they assign provide a standard against which others (eg. students and teachers) are judged. The meanings assigned by experts change over time as new knowledge becomes available.

Resolving Inconsistencies Understanding implies internal consistency in our explanatory systems. To understand requires that potential inconsistencies and contradictions in our views (e.g. Darwinian vs. Lamarckian theories) be resolved. Resolving inconsistencies is most often a time-consuming and energy-expending process that demands significant structural changes in an individual's framework of knowledge.

Seeking Simplicity The explanations offered by experts in scientific disciplines are parsimonious; that is, they lack extraneous or unnecessary descriptions. The principle of parsimony, sometimes referred to as Ockham's Razor, suggests that the best explanations in natural science tend to be relatively sparse. Experts in scientific disciplines sometimes suggest that understanding is revealed in the simplicity, 'elegance' and 'beauty' of an explanatory system or model.

Thinking Critically Those who understand scientific phenomena are able to use their knowledge to think critically about explanations offered by others, and to look for flaws in their own thinking patterns. In doing so, experts evaluate the knowledge and value claims of other scientists; examining and assessing the underlying assumptions, premises, methodological manipulations and logical reasoning strategies.

Figure 1 *Understanding understanding.*

Novak's concept maps

Getting students to reveal their understanding of complex conceptual domains such as photosynthesis has proven to be a real challenge for biology teachers. One technique that has proven itself over the last 25 years is the concept map (Novak and Gowin, 1984; Novak, 1998).

A concept map is a two-dimensional node-link representation that depicts the most important concepts and relationships in a knowledge domain. As developed by Novak and Gowin, the technique produces a hierarchical schema that is particularly revealing and especially useful in diagnosing conceptual errors and faulty reasoning.

We have used concept maps with students ranging in age from seven or eight (early elementary school) to senior citizens. The technique is easily taught and lends itself especially well to biology and other 'conceptually-rich' knowledge areas. Students may learn to do a concept map in a relatively brief period of time, including opportunities for practice and feedback. Experience has shown that opportunities for feedback and remapping are essential if high levels of 'mapping proficiency' are desired. Many studies have shown the technique to be a valid and reliable measure of what a student understands (Shavelson and Ruiz-Primo, 2000).

Normally the student is asked to construct a map of a circumscribed area of knowledge but, occasionally, it is useful for a teacher to draw a map based on discussions with a student. In Figure 2, Professor Novak has attempted to capture some of Jon's (a seventh grade student) ideas about photosynthesis in the form of a concept map.

In this map Professor Novak depicts the major concepts within Jon's explanatory model. They are *wood, water, minerals, soil,* and *photosynthesis.* The missing ideas are *cellulose* and the *weight of carbon dioxide.*

All things considered, the concept map is perhaps the most powerful assessment strategy we have for exploring and documenting the structural complexity and propositional validity of knowledge in scientific domains. We caution, however, that this tool, if it is to realise its significant potential, must be imbedded within and implemented directly into the instructional process, and not used simply 'after the fact' as an assessment device. This requires that students and teachers begin to understand the critical importance of prior knowledge and misconceptions, and their role in subsequent learning. In this context, the concept map should be recognised for what it is; a powerful tool for depicting 'cognitive deficiencies' and an aid in modifying and building complex, scientifically valid knowledge structures in the natural sciences. Good software for constructing online concept maps is available from the Institute for Human and Machine Cognition (IHMC) at the University of West Florida, and may

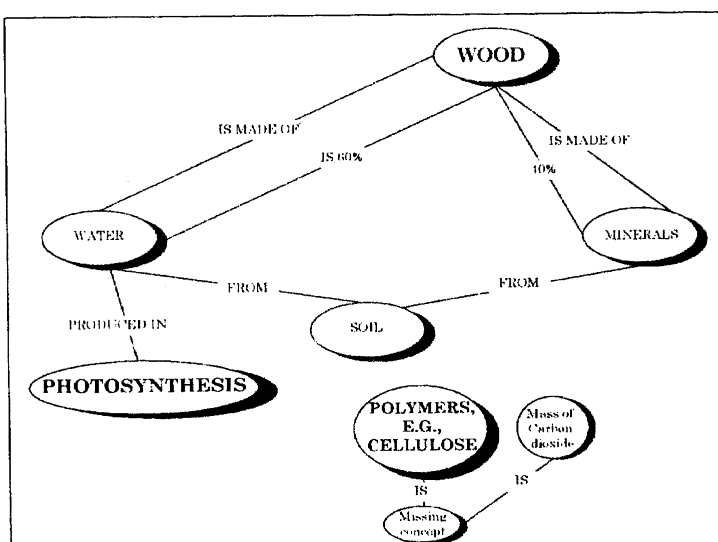

Figure 2 *Jon's idea about plant nutrition: a concept map drawn by Professor Novak (Mintzes et al., 1997).*

be downloaded free of charge for nonprofit use at: **http://cmap.coginst.uwf.edu.**

Gowin's V diagrams

V diagrams offer a way of assessing critical thinking skills and knowledge about the scientific process. Because they are substantially new to most students, we usually recommend that instructors begin assessment with concept maps and then proceed to the use of V diagrams after students are comfortable with the terminology they employ.

Normally, in performing a laboratory experiment or reading about an experimental procedure, we supply students with an outline, incomplete V diagram giving and defining the nine categorical elements it depicts (Figure 3). The students are then challenged to complete the diagram individually or in small groups with their laboratory partners.

In our own courses we often integrate readings from the history of biology in order to acquaint students with the personal characteristics of the scientists, and the thought processes and experimental manipulations they undertake. In this example we depict a V diagram of Von Helmont's famous willow tree experiment of 1660. This experiment is particularly useful partly because the conclusions Von Helmont drew are inconsistent with our current understanding of photosynthesis and the principal source of biomass in growing plants. In this way we try to help students understand the non-linear nature of scientific discovery and to encourage them to recognise that even our most illustrious predecessors erred in their reasoning about natural phenomena. It is interesting to note that Von Helmont did not know that carbon dioxide exists and that it has weight that becomes part of the plant mass, the same faulty understanding evidenced by Jon (Figure 4).

V diagrams help students and teachers understand the constructed nature of knowledge and the complex cognitive and affective elements that interplay in designing an inquiry and interpreting the results. When students use V diagrams to plan inquiries and to report on them, they begin to understand what *constructivism* is all about. As with concept maps, it is important that students be introduced to the V diagram procedure in the context of daily classwork so that the technique becomes a 'integrated' learning and knowledge building tool rather than an artificial and disconnected assessment device.

Fisher's SemNet software

Another knowledge representation tool that utilises computer software is SemNet. Developed and tested extensively by Kathleen Fisher and her colleagues at San Diego State University, this Macintosh-based program allows students to identify the many concepts in any domain of study, such as biology, and to see multiple ways of relating these concepts. Use of SemNet and other computer-driven techniques in state or national testing will probably not be practicable until computer-based testing is widely instituted and accepted, and this may be some years into the future. Nevertheless, SemNet is a tool that can facilitate classroom learning and also be highly effective in classroom assessment (Fisher, 2000). The SemNet program is available free of charge for use in non-profit organisations at: **http://trumpet.sdsu.edu/semnet.html.**

Wandersee's image-based tests

Over the past 20 years Wandersee's research group at Louisiana State University has been experimenting with a variety of graphic and image-based assessment strategies. His efforts grow out of the recognition that biological and other kinds of knowledge are most probably dually-coded in our memory systems (Paivio, 1991), as language-like propositions and picture-like mental representations. Furthermore, most biology textbooks and other instructional materials make wide-spread use of photographs, line-drawings, and other visual and graphic depictions. Research evidence suggests that students who make use of these learning aids tend to evidence greater understanding (Wandersee, 1988).

Based on these considerations, Wandersee (2000) has suggested that image-based assessment strategies serve several purposes that only partially coincide with other ways

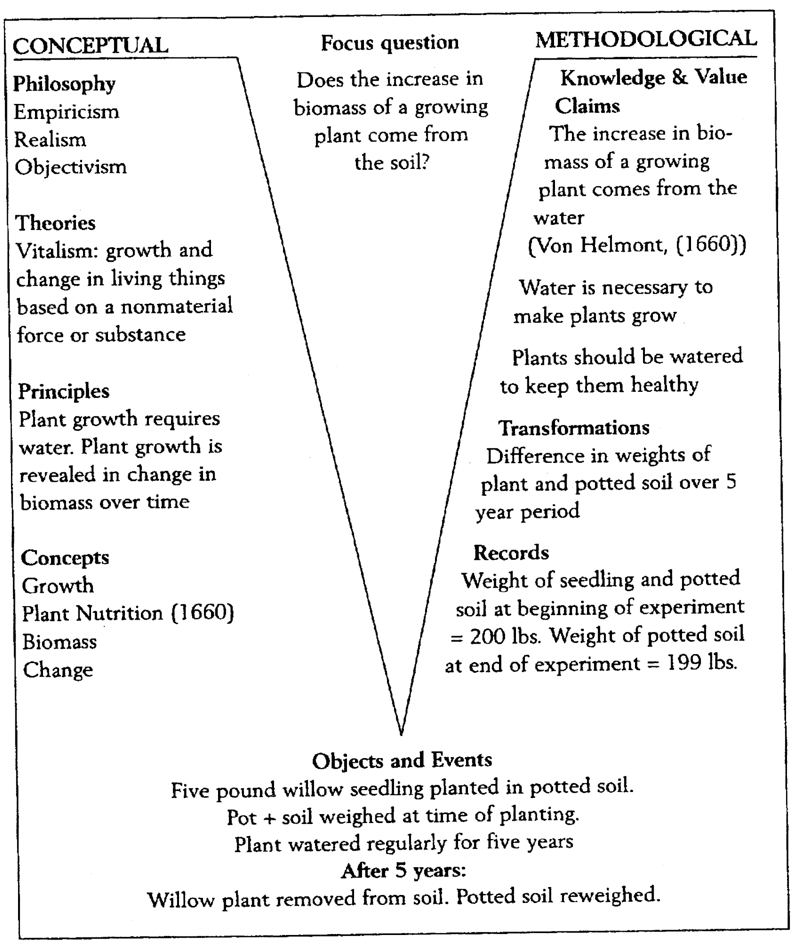

Figure 3 Von Helmont's experiment: A V diagram.

Prior to Instruction

Interviewer: '... how much do you think that [log] weighs?'

Jon: 'I'd say about as much as a newborn baby....about ya know...5 – 6 pounds just as an average.'

I: 'What did it need to grow?'

J: *'Number one water....all plants and animals need water....it's a basic thing of life; sunlight.....soil.....minerals from the soil.....I guess that's about it, basically...'*

[Six days of instruction on photosynthesis, including three laboratory sessions]

After Instruction

J: *'The air is part of a cycle called photosynthesis. It helps to make energy for the plant...'*

I: 'OK and what is it using from the air?'

J: *'It's mainly using carbon dioxide...'*

[Jon writes correctly balanced equation for photosynthesis]

I: 'Now, last time you said the tree is made of about 60% water and 40% soil minerals.....what would you say now, if I asked you...'

J: *'Sixty percent water and forty percent all the rest.... definitely.....70 –75% water'*

[Teacher observing Jon on tape: *'I don't know what happened....I thought I made it clear....I tried to draw it together...'*]

I: 'You mentioned carbon dioxide and you mentioned oxygen...do you have any concept of what these are?'

J: *'Elements that help things grow and move...and make food'*

I: '...think they have any kinda weight...do you think?'

J: *'no, nope....cause if they had any weight you and I couldn't breath them in...'*

Figure 4 Where plants get food: an interview with Jon and Teacher (Schneps, 1996)

of probing understanding of scientific concepts. He suggests further that 'well-chosen photographic images can serve as an alternative cognitive portal for accessing what the learner understands about a given biological topic' and that both verbal and mixed verbal/visual test items provide a more complete picture of knowledge stored in long-term memory.

Wandersee's ideas are embodied in a type of test item that he calls the 'Twenty Question (20-Q) Model' (Figure 5). The model suggests a series of questions that probe understanding elicited from a visual image or photographic depiction. An example of such an image is given (Figure 6) which depicts Von Helmont's classical seventeenth century experiment on the source of biomass in a growing plant. As a result of the experiment, Von Helmont concluded (inaccurately) that the increase in biomass is a result of water taken in by the plant. Questions about the image might include:

- Describe this event biologically.
- What biological principle is operating here?
- In the past, how was this event explained by scientists?
- Make a biological estimation of how long it would take for the plant to grow to 225 kg (500 pounds).

Piaget's clinical interviews

In his pioneering work, Piaget developed what he called the 'clinical interview', a technique that provides insights into how

- Describe this event biologically...
- Give the function(s) of this/these structure(s)...
- Provide the next step in this process...
- How else could this event be explained biologically...
- Predict what will happen next...
- What evidence do you see that suggests...
- What is the limiting factor in this process...
- What biological principle is operating here...
- If we didn't have or couldn't use...what could we use instead...
- What is the connection between...
- In the past, how was this event explained by scientists...
- On what basis do you suspect this organism is a...
- Biologically, this organism is related to...
- How would you go about measuring...
- Make a biological estimation how long it would take for...
- What is the concept a biologist would use here...
- Ask an important question about this photograph...
- What would a ...graph of this event look like...
- Design a device to monitor an important variable in this environment...
- Apply what you read in your last assignment to this photo...

Figure 5 Wandersee's twenty questions.

individuals think about specific problems. Modifications of Piaget's technique are now widely accepted as the 'gold standard' for ascertaining an individual's understanding of a particular activity, topic, or concept. A variety of protocols for interviewing have been developed, but most involve posing questions and then probing the respondent's answers with follow-up questions to gain a complete understanding of the interviewee's views. It takes some time and practice to develop good interviewing skills, but this is a procedure for which all biology teachers should develop competence. Suggestions on 'how to interview' can be found in many sources (see, for example, Novak and Gowin, 1984; Mintzes *et al.*, 2000).

Clearly classroom teachers haven't the time to interview every student on every topic; however, brief interviews (5 – 10 minutes) with individuals or small groups can 'provide an overall portrait of the various understandings that the students in a class might hold' (Southerland *et al.*, 2000). In this context the interview offers a kind of 'formative' assessment tool that is enormously helpful in judging how well instruction is succeeding.

Engaging students in dialogue is perhaps the oldest, most direct, and reliable way of judging understanding. The continued reliance on 'oral examinations' and 'thesis defences' at the graduate level in our best universities is a good indication of the value and implicit confidence we place in these techniques. When done well, these interactive approaches enable us to probe deeply into a student's way of thinking.

In a recent interview with Jon, a seventh grade student attending a public middle school in the Boston area, we queried him before and after instruction about the source of the biomass in a large log. Before instruction, Jon seemed to believe that

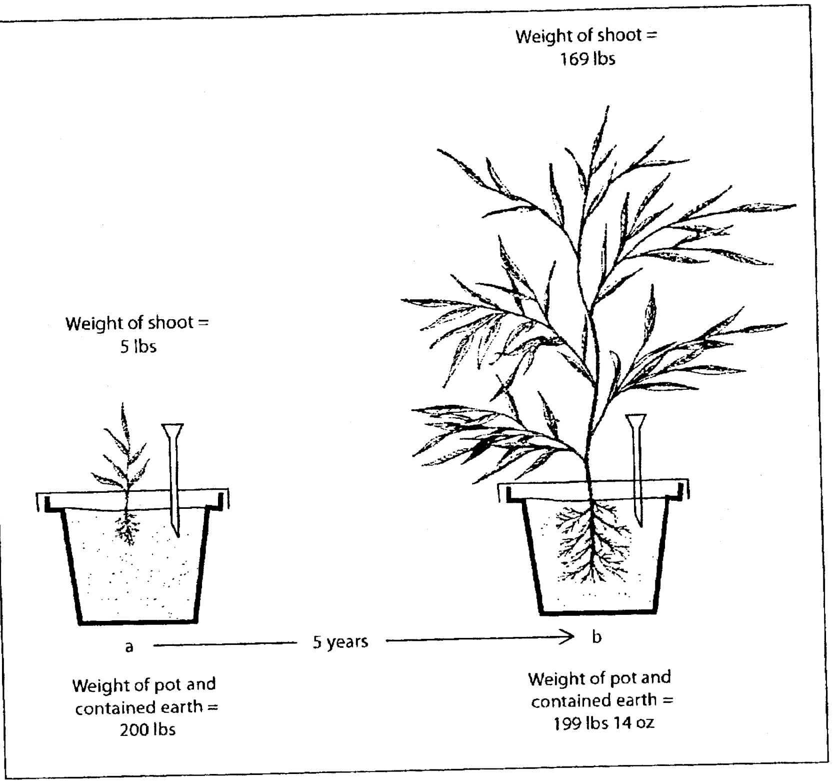

Figure 6 An image-based test item.

plant growth depends primarily on water, sunlight, and minerals from the soil. He makes no mention of carbon dioxide (or oxygen) or its role in photosynthesis. We interviewed him again a few weeks later to see if his ideas had changed as a result of the six class sessions his teacher devoted to the topic. Later, Jon's teacher, Mr H, watched our videotaped interview and commented on his student's performance.

A review of the partial transcript (Figure 4) shows that Jon did indeed learn a few isolated pieces of knowledge about photosynthesis, e.g., it is a photochemical cycle; it uses carbon dioxide; it 'makes energy' for the plant. But, significantly, he has failed to put these pieces together into a coherent framework and, even though he is quite capable of scribbling down a correctly balanced, overall chemical equation, he fails to recognise the central role of carbon dioxide and its conversion into structural (and storage) elements of the growing plant.

Watching this sequence, Mr H is aghast at Jon's failure to grasp one of the most important points in his lessons, but can't pinpoint the source of his conceptual difficulties. Later in the interview it turns out that Jon's problems are apparently rooted in some fundamental misconceptions about the particulate nature of matter and the mass of gaseous substances. This assessment sequence illustrates a common finding in science learning research; namely, conceptual problems are often deeply-rooted and not easily exposed.

Portfolio assessment

Biology teachers often use laboratory reports, book reports, and written research assignments as assessment measures. These and a variety of other 'work samples' may be included in student portfolios which can serve to document actual performance in classroom, laboratory, and field-based activities. Student artwork, photographs, songs, poems, concept maps, V diagrams, flow charts, field notes, and textbook assignments are all examples of the kind of work products that may serve as evidence of understanding. Collections of work samples offer a degree of flexibility for instructors, and enable students possessing a broad range of individual talents and abilities to be rewarded for their strengths and efforts. Vitale and Romance (2000) have suggested that portfolios are most useful when they focus squarely on those elements of student work that provide tangible evidence of successful knowledge construction. To this end they recommend the use of concept maps in the planning and implementation of portfolio assessment tasks. The IHMC concept mapping software can serve as an excellent platform for portfolios in that it provides for adding icons to concepts that can be clicked to obtain the full range of resources included in portfolios and also URL's for Internet resources. All of these become integrated into a coherent conceptual whole.

Written products

Writing has been and will remain an essential way of recording and expressing scientific ideas. Writing assignments, when carefully designed, can and should be an important adjunct to other forms of assessment in biology. Unfortunately, written assignments such as research reports, journals, and expository themes are used less frequently by many teachers because the time required to read and evaluate these products is often viewed as prohibitive. This is especially unfortunate in light of the new focus given by internationally prominent linguists, sociologists, and educators on the significance of written discourse as an essential element in the development of scientific literacy (NRC, 1995). Champagne and Kouba (2000) rightly stress the critical role played by discursive activities in scientific understanding and the ability to reason and inquire. In our view, writing should be an integral part of every school science experience.

Performance measures

Biology teachers have long recognised the importance of performance as a significant indication of understanding. The laboratory-based 'practical examination' is a well-recognised and widely used assessment of performance in biology. Traditionally these practical tests have focused largely on issues of structure and function, the appropriate use of laboratory equipment, and the design of experiments and interpretation of research findings. More recently, performance assessments have posed 'holistic' tasks or problems in which students are asked to use their

knowledge to plan and carry out an experiment and make sense of the results; e.g., the sow bug's (woodlouse's) choice of light versus dark environmental conditions (Shavelson and Ruiz-Primo, 2000). The assumption is that this form of assessment probes deeply into both the *declarative* (knowing what) and the *procedural* (knowing how) components of a student's knowledge structure. In Shavelson's system, each performance assessment consists of:

(1) a *task* which poses a potentially meaningful problem and requires the manipulation of concrete materials;
(2) a *response format* that formalises the students' reporting;
(3) a *scoring system* that enables professionals to judge the reasonableness of the students' answers.

Conceptual diagnostic tests

One of the important products of the broad-based research effort on students' 'alternative conceptions' in science (Wandersee *et al.*, 1994) has been a range of diagnostic assessment tools that focus on a single concept or a small set of related concepts. Many of these instruments employ traditional psychometric approaches such as 'multiple-choice' items (Sadler, 2000), but differ from conventional tests in that the items reflect what students themselves understand about a scientific idea. To learn more about these tools, examine the Field-Tested Learning Assessment Guide (FLAG) website of the National Institute of Science Education (NISE) at: **www.wcer.wisc.edu/nise/cl1/flag.**

Conclusions and recommendations

> 'Plato dreamed of a rational world ruled by philosopher-kings. Terman revived this dangerous vision, but led his corps of mental testers in an act of usurpation. If all people could be tested, and then sorted into roles appropriate for their intelligence, then a just, and, above all, efficient society might be constructed for the first time in history' (Gould, 1981).

Until very recently assessment and evaluation in school science has served, among other functions, principally to sort and select those students from among the school-age population who have the 'aptitude' and interest to continue into advanced courses and programs in science-related disciplines. Schools, colleges, and universities served as efficient portals into the higher realms of science and technology, and evaluation served to identify individuals with the 'talent' required to perform successfully in those roles.

Assessment tools developed and honed during the 20th century performed these purposes well. Unfortunately, standardised testing, based on the model of the *Stanford-Binet Test* and similar 'objective' measures of academic achievement and intellectual ability (*Scholastic Aptitude Test, Graduate Record Examination, Law School Admissions Test, Medical College Admissions Test*), were widely copied by classroom teachers and soon became the *sine qua non* of evaluation. It is now clear, however, that these methods of assessment, no matter how useful they may be as predictive measures, are of little value to classroom teachers who wish to encourage meaning making and conceptual *understanding*. It is our view that *understanding* is not meaningfully revealed through 'normalised' comparisons among students, and that conceptual change is not adequately represented by a single, 'standardised' alphanumeric score on any test.

Instead we believe that good assessment practice must be built on a strong and intellectually defensible theory of science learning and knowledge construction (Mintzes *et al.*, 1998). No single assessment technique by itself adequately reflects the entire multidimensional nature of understanding. Longitudinal assessment efforts that focus on knowledge restructuring are preferable to one-time measures of subject matter attainment. With these thoughts in mind, we would like to close this paper with a modest set of concrete suggestions for improving classroom assessment practice in biology. Specifically, we suggest that teachers:

- reduce reliance on testing methods that reward and reinforce rote learning of verbal knowledge (including multiple-choice, true-false, matching, and fill-in questions) and the application of algorithmic (memorised step) solutions to problems;
- begin to imbed assessment efforts 'seamlessly' into the instructional program so that the distinction between learning and evaluation becomes less stark;
- focus assessment efforts on student constructed 'work products' including concept maps, V diagrams, written and oral reports, artistic performances, and computer-generated efforts;
- make special provision for assessing the efforts of students who have special talents and those who excel in learning through non-verbal (i.e., visual) modalities;
- avoid 'one-shot' assessment techniques in favour of methods that encourage multiple iterations of the same or similar tasks over extended periods of time;
- consider the use of collaborative or co-operative assessment methods in which teams or small groups of individuals work together on a product that demands division of labour or specialisation of knowledge;
- for further suggestions see Mintzes *et al.*, 1998; 2000.

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