A CONCEPT INVENTORY FOR MOLECULAR LIFE SCIENCES: HOW WILL IT HELP YOUR TEACHING PRACTICE?

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Textbooks for biology are getting bigger and bigger with each edition, but does this mean that our students are learning more? Most of us would answer no to this question. In fact, the learning by our students is sometimes seen as disappointing, as the core concepts or the 'big ideas' of biology appear to be obscured by rote learning of detailed content. Educators have recognised that the information explosion in biology, particularly in the molecular life sciences, has created a significant problem in selecting what core concepts and principles we should be teaching our students (1). Another consequence of the focus on specific content in the structure and assessment of many secondary and tertiary biology courses is that students obtain little idea of the nature of science and may come to see science as a collection of unchanging facts to be learnt. In addition, the molecular life sciences are becoming more interdisciplinary, more systems-focussed and increasingly dependent on chemistry, physics and maths. In considering these issues, it is timely to remember the educational philosophy expressed by A.N. Whitehead in 1929 (2), "Let the main ideas which are introduced into a child's education be few and important, and let them be thrown into every combination possible. The child should make them his own, and should understand their application here and now."

Focussing on the main ideas is clearly what we should be doing in the molecular life sciences, but learning at the conceptual level is harder to achieve and to assess than the learning of content knowledge. As it is no longer possible to cover everything, we must choose - what are the most important aspects of biology that a student really needs to be familiar with? What skills do students need to be able to cope with the changing face of biology? How are we going to teach both the content and the skills? How will we assess whether the student has in fact mastered the crucial ideas? We would benefit from a validated curriculum framework and from educational research providing evidence on what we should teach our students. One way to address these challenges is by using a concept inventory, which is a standardised test that aims to examine student understanding of previously identified core concepts or big ideas. Results from such tests allow a greater understanding of the nature of student difficulties, which in turn can lead to the development of more effective teaching and learning strategies. Our project aims to begin developing concept inventories for the molecular life sciences and is funded by the Australian Teaching and Learning Council and the International Union of Biochemistry and Molecular Biology (IUBMB).

It is clear from the education literature that students often construct their own understandings that are at odds with scientific concepts (3). These unscientific conceptions, sometimes called 'misconceptions' or 'alternative conceptions', can interfere with the learning of correct scientific ideas. Thus for teaching to be effective, it is important to try to identify students' unscientific conceptions and ways of reasoning and then devise appropriate teaching strategies to remediate them (4). This is where the concept inventory plays a role. A well-designed set of questions will provide essential information on what students think and on their ability to use core concepts. Concept inventories differ from assessment tests in several important ways: they are aimed at examining conceptual understanding; they may not cover detailed content knowledge; they are based on rigorous research into student misconceptions; and questions are often worded to reflect common student misconceptions (5). Results from the use of concept inventories provide information on levels of student understanding and also allow an assessment of the effectiveness of teaching (for example, the same test may be used pre- and post-instruction). Most importantly, the information obtained also can be used to improve teaching and curriculum design, for example, by providing feedback to students and by informing the design of remediation strategies to correct students' conceptual and reasoning difficulties.

The effectiveness of a concept inventory has been well documented in disciplines other than biology. The idea of a concept inventory first arose in physics education more than fifteen years ago through the work of David Hestenes and his graduate students at Arizona State University (6), who wrote a test covering the conceptual basis of mechanics (the Force Concept Inventory) and administered it to their introductory physics course. To their dismay, their students failed on questions that the lecturers and tutors thought 'trivial'. One study showed that, at the beginning of the course, 80% of students could state Newton's third law but at the end, only 15% could demonstrate that they actually understood what it meant (7). This was despite the fact that many of the same students performed well on exams, indicating a lack of alignment between the standard assessment tools and the lecturers' objectives.

The Force Concept Inventory, which has now been extensively validated and widely used, has provided a model for the development of concept inventories that have been used in a variety of fields, particularly in physics and engineering, to provide invaluable information for both students and their teachers (8). One advantage of a good concept inventory is that it not only identifies failures in student understanding, but can also be used to assess the effectiveness of teaching strategies designed to remediate these difficulties. Again, this has been abundantly demonstrated in physics, with results from tests performed pre- and post-instruction leading to the conclusion that a number of different 'interactive engagement' teaching approaches result in increased student understanding (9-12). Thus a concept inventory paves the way for educators to gain a greater understanding of student difficulties, which should then lead to more effective teaching and learning strategies, and for researchers to obtain new and needed knowledge about student learning.

So where does this leave biology? It is hoped that the development of concept inventories for the molecular life sciences will bring about a transformation of education in our discipline, similar to what has occurred in physics. Development of concept inventories in biology has lagged behind other sciences, but there are now a number of projects underway. In addition to ours, several other projects are addressing specific areas or topics where research into students' understanding has identified conceptual difficulties (for reports from two meetings on conceptual assessment in biology, see http://bioliteracy.net/ and references 5 and 13). The remainder of this article will focus on our concept inventory project. A first step in developing a concept inventory is deciding on the core concepts that a student needs to understand. This is surprisingly difficult to articulate. There is considerable variation in what is covered in introductory biology courses and many concepts that underlie the molecular life sciences are, of course, those of chemistry and physics. We began by attempting to generate a list of 'big ideas' in biology that could be used as a conceptual framework to direct our thinking on question coverage and design. A big idea should (a) be at the heart of expert understanding, (b) be inherently abstract, with the meaning not always obvious to students, and (c) serve as an organiser, connecting concepts, and be applicable in a range of topics in the subject (**Fig. 1**).

Our strategy in designing questions was to use the big ideas to help us think about what is important for a student to know, rather than testing the big ideas directly. Each idea will have relevance to more than one topic or

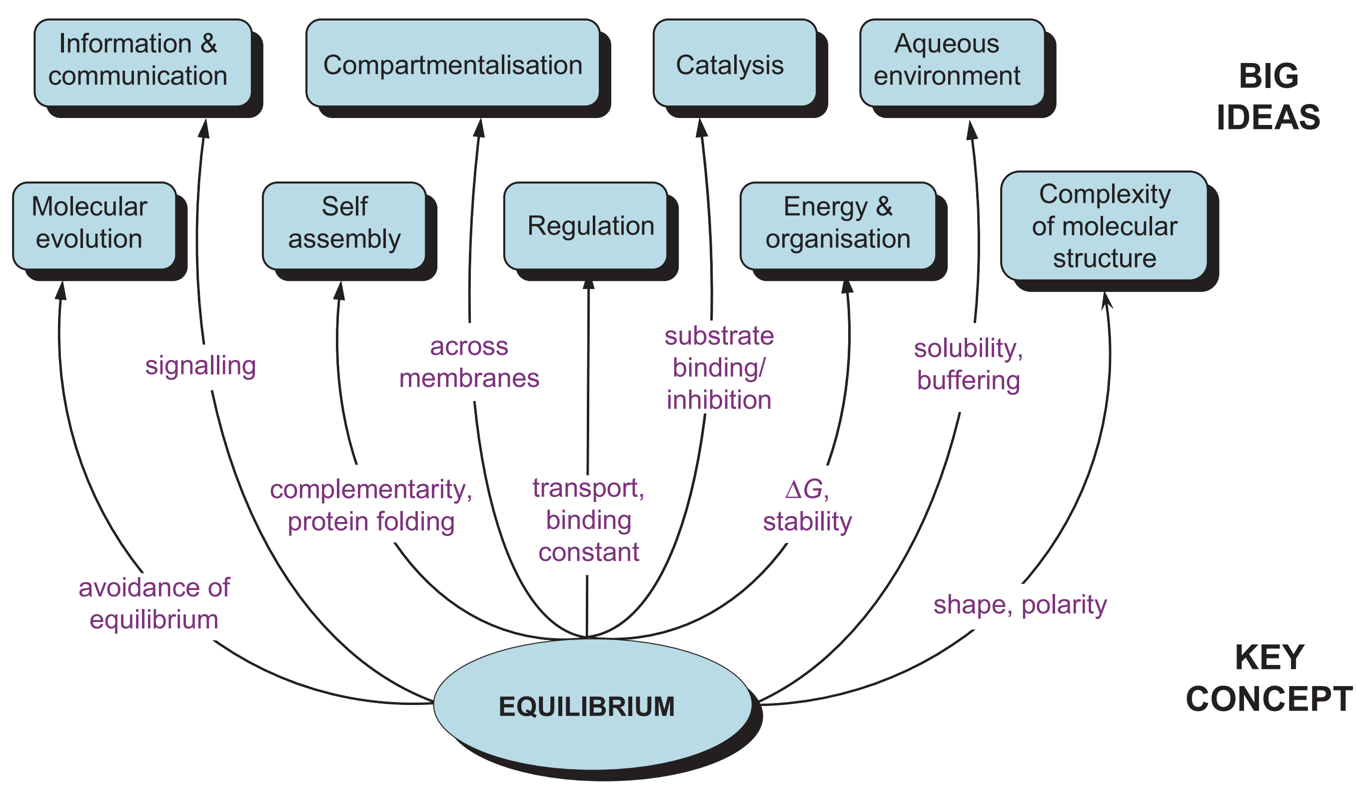


Fig. 1. The big ideas of the molecular life sciences. Also shown is the relationship between one key concept, equilibrium and the big ideas.

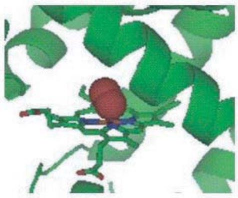
content area, so our next step was to think about concepts and how they fitted into each big idea. This then led to content areas where this conceptual knowledge was needed, which provided a context for question design. For example, we looked at the concept of equilibrium. It is clear that this has relevance to many of the big ideas, as shown in **Fig. 1**, and therefore is a concept that is fundamental to the molecular life sciences.

There are a number of factors to consider in designing concept inventory questions. The questions must be based on rigorous research into student misconceptions. They should avoid the possibility of a rote-learned answer, because we want to test student understanding of a concept (which should include the ability to unpack and apply that concept), rather than the ability to memorise information. Thus it is important to provide a context, so the student can relate the question to what they have learned while requiring that the student apply their knowledge. Questions should be presented in student, rather than expert, language, as the aim is to find out what the student thinks, not whether they can correctly identify a textbook answer. A particular concept should also be presented in several different contexts to determine if the student has a level of understanding that allows them to apply their knowledge to different situations (a crucial ability in science). We also need to take into account what other skills a student might need to interpret questions; for example, are we expecting students to interpret diagrams or graphs and is it possible that an incorrect answer may be due to deficiencies in these skills rather than a lack of understanding of the concept? Finally, questions are usually multiple choice or true/false, so that test results can be validated and compared easily and can then be widely used by the community of educators. This has proved crucial in physics education (12).

In dealing with the concept of equilibrium, we have developed a series of questions in three different contexts: ligand binding (**Fig. 2**); buffers; and enzyme kinetics. These questions are currently being tested in two ways. Firstly, we have given the test (as a non-assessed activity) to 210 students at the University of Queensland, with further testing underway at the Australian National University and internationally. This allows us to see whether our questions are pitched at the right level and cover a range of student understandings. For example, thinking that statement (b) in **Fig. 2** is correct reflects a naïve understanding of the interaction between myoglobin and oxygen, but this is clearly held by many students. This suggests that students do not have a good working understanding of equilibrium. Secondly, we have interviewed students about why they chose their answers and some examples are shown in **Fig. 2**. This is particularly important, as it gives us insight into the underlying thinking and tells us whether students are interpreting the questions in the way we think they are. This research into student conceptions and misconceptions is an essential aspect of the development of a concept inventory and will lead to a greater understanding of student thinking, as well as refinement and improvement of questions.

At this stage of our project, we are designing and testing more questions on several different concepts, including protein structure and metabolism. Once we have sets of questions that have been tested internationally and validated by interviews to show that they do reflect common student misconceptions, we aim to make the test available in a secure, web-based format similar to the Force Concept Inventory in physics. This will provide a resource for all educators in the molecular life sciences, enabling them to test their own students. We hope that a greater understanding of student difficulties will lead to significant pedagogical improvements, which in turn will produce improved student learning outcomes. We are also interacting with other concept inventory researchers focusing on different areas and hope to pool resources, allowing more rapid development of more comprehensive question banks. A workshop to facilitate this was held at the 33rd FEBS/11th IUBMB Conference held in Athens earlier this year and the future of concept inventories in biology looks promising.

Question One



Myoglobin plays an important role in oxygen storage in muscle. Under physiological conditions the equilibrium between Mb and MbO_2 is reached very rapidly.

For each of the following statements choose a response: **true, false** or **don't know**.

a) Myoglobin binds oxygen (O_2) and is able to release it chemically unchanged.	True	78% correct
b) Each oxygen molecular remains bound to a myoglobin molecule until it is needed.	False	23% correct
c) Oxygen is released more easily from MbO_2 when the concentration of oxygen is low because the oxygen is bound more weakly to the Mb.	False	43% correct

Comments about question (b) from student interviews

Second Year Student (TRUE): *"I answered that as true because my understanding is that the oxygen remained in an ionic bond with the myoglobin until there was a depletion in oxygen concentration in the tissue."*

First Year Student (FALSE): *"That's not true because it's an equilibrium so it's constantly going backwards and forwards, you know, if it was just needed then it wouldn't be in equilibrium, it's like a constant process. That's how I thought about that one."*

Fig. 2. A sample question set on equilibrium, showing the percentage of students who answered each question correctly, and some comments from students.

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