Assessing student understanding in the molecular life sciences using a concept inventory

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Concept inventories are rigorously validated web-based multiple choice instruments that are designed to evaluate the nature and quality of student understandings of key concepts. Such tests can also reveal any related alternative conceptions and visualization difficulties, thereby providing educators with vital feedback about their students' learning and, in turn, their own teaching practice and pedagogical content knowledge. Students receive rapid diagnostic feedback on their understanding of key concepts and remediation can be targeted by the educator towards problematic areas. This paper describes the process that is being used to develop and validate a concept inventory, which is tailored for use by instructors teaching introductory university courses in biochemistry and molecular biology. The initial phase of the project has involved the identification of the concept domain through a set of "Big Ideas" which are unique to the molecular life sciences and which capture, in a comprehensive and future-looking way, thinking by experts in the field. In the second phase of the project, a draft set of key concepts that underpin understanding of these "Big Ideas", and which are at an appropriate level of discreteness and specificity to be tested through the concept inventory, has been identified. These include equilibrium, protein structure, metabolic energy and coding of information. A refined set of adaptive questions has been developed around the key concept of chemical equilibrium. Statistical tools to analyse questions for reliability and validity have been trialled and a series of interviews has been conducted to examine students' alternative conceptions. A second set of questions on protein structure has been developed and is currently being refined as an adaptive test.

Keywords: *concept inventory, diagnostic assessment, molecular life sciences*

Introduction

Diagnostic assessment tools which are designed primarily for use by educators to inform their teaching also provide a potential means of engaging students productively in formative assessment tasks. The student not only receives rapid feedback on their overall understanding of important concepts, but also receives the benefit of any remedial teaching identified as necessary by the educator.

The idea of a concept inventory arose in physics education through the work of David Hestenes and his graduate students (Hestenes, Wells, & Swackhamer., 1992) who wrote a test covering the conceptual basis of mechanics and administered it to their introductory physics course. To their dismay, their students failed on questions that the lecturers and tutors thought "trivial". At the same time, Harvard astrophysicist, Philip Sadler was starting the Private Universe Project (*Private Universe Project in Science*, 1995) in which he interviewed new science graduates at ivy league universities about central ideas in science that are critical to scientific literacy, such as the model of the solar system that explains the seasons, and the molecular model of the air that allow us to understand how the mass of a tree is derived from carbon dioxide. These interviews showed that, in many cases, the majority of students had failed to learn central concepts during their undergraduate programs. 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. Subsequent to development of the physics Force Concept Inventory has provided a model for the development of tests that have been used in a variety of fields, including chemistry, physics, engineering, astronomy and evolutionary biology, to provide invaluable information for both students and their teachers (Richardson, 2005).

Our interest has been to apply what has been learnt from work in these disciplines, to the development of a concept inventory for the molecular life sciences. We are targeting the instrument to undergraduate students with a background in introductory chemistry and biology, who are undertaking their first course in molecular life sciences. This presents a challenge that has not been addressed in previous inventories: the challenge to identify a set of key concepts that educators in general agree are fundamental to the discipline and worthy of testing at a conceptual level. The reason that this is a topic for current debate in the molecular life sciences is that the discipline has experienced exponential growth in knowledge in the 20th century. This has led educators to pose the question, "What constitutes core knowledge in our discipline and which concepts are fundamental to our subject and should be the focus of undergraduate curricula?" (*BIO 2101: Transforming Undergraduate Education for Future Research Biologists*, 2003). In addition to this explosion of knowledge, research in the biological science has moved towards the study of complex systems. The links between biology, chemistry, physics and mathematics have strengthened along with these developments.

The first stage of our project has therefore involved the definition of the concept domain for molecular life sciences, through a set of "Big Ideas" which are unique to the molecular life sciences and which capture, in a comprehensive and forward-looking way, thinking by experts in the field. These Big Ideas are serving as a theoretical framework for the remainder of the project. The second stage has involved the development of a draft set of key concepts that underpin understanding of these "Big Ideas", and which are at an appropriate level of discreteness and specificity to be tested through the concept inventory.

The third stage has been the development of a refined set of adaptive questions around one of these key concepts: chemical equilibrium. Statistical tools to analyse questions for reliability and validity have been trialled and a series of interviews has been conducted to examine students' alternative conceptions of the concept.

Test Development

In framing our list of Big Ideas for the molecular life sciences, we have used the characteristics of Big Ideas as articulated by Wiggins and McTighe (Wiggins & McTighe, 2005), as criteria by which to evaluate a wide range of possible Big Ideas gleaned from text books, research literature, existing curricula and discussion with experts in the field of molecular life sciences. These characteristics are:

- Providing a focusing conceptual lens for any study
- Providing breadth of meaning by connecting and organising many facts, skills and experiences; serving as the linchpin for understanding
- Pointing to ideas at the heart of expert understanding of the subject
- Requiring “uncoverage” because its meaning or value is rarely obvious to the learner
- Having great transfer value – “horizontally” (across subjects) and “vertically” (through the years in later courses)
- Specific to the field (molecular life sciences)

The draft set of Big Ideas thus developed, was circulated to experts in the field (educators and research scientists) for comment. The revised set (see Figure 1) is forming the framework for the remainder of the project. Note that in the full statement of Big Ideas, each one- or two-word idea is accompanied by a sentence encapsulating a brief explanatory statement (not shown in the Figure).

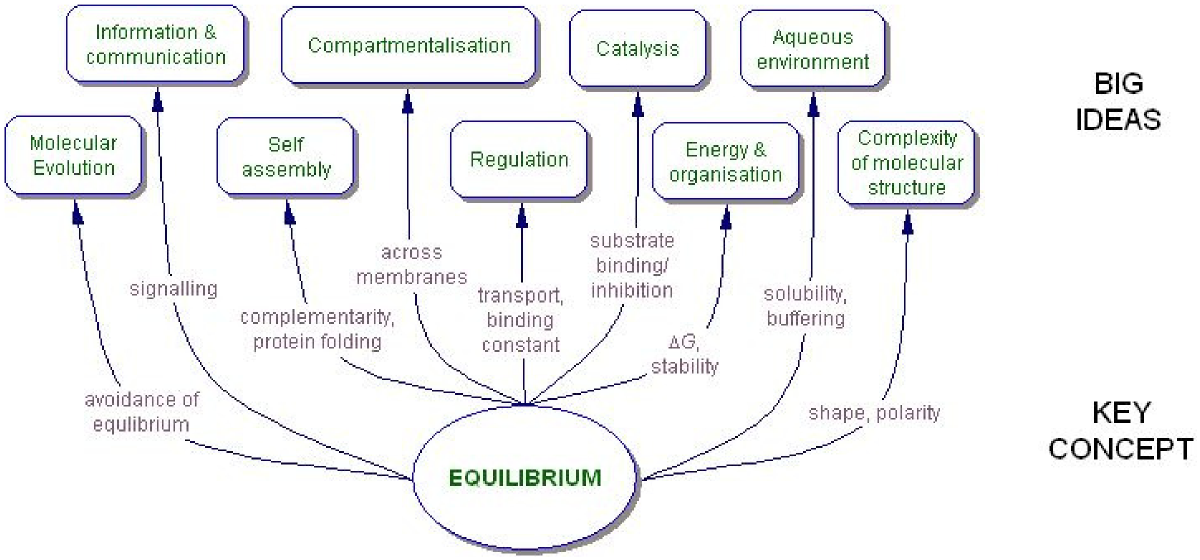


Figure 1. Mapping of a key concept (equilibrium) to the Big Ideas

Using this list, and with reference back to text books, curricula and other literature, we have determined a set of key concepts which, while not comprehensive, provides a good starting point for the development of a concept inventory for the discipline area. Each of the key concepts identified as useful for testing, for example equilibrium, underpins understanding across all or most of the Big Ideas as shown in Figure 1.

The goal in setting questions was to arrive at a coherent set of questions that tested understanding of each key concept. This requires that questions are developed across a range of contexts relating to each concept and that only a single concept is tested in each set.

The process for developing questions has been as follows:

1. A search of the literature for relevant information on alternative conceptions
2. Choice of a small number of appropriate biochemical contexts for framing questions, based on typical introductory biology/chemistry curricula
3. Setting a series of true/false items around each context, taking account of identified alternative conceptions
4. Trialling the draft items (~25) with students at different levels. Statistical analyses were undertaken to ascertain whether the items were testing a single concept, the level of difficulty and the extent to which the item discriminated between students who had completed their first biochemistry course and students who had not yet commenced. Interviews with individual students were undertaken to further explore student understandings and alternative conceptions
5. A set of ~15 refined items was developed based on the statistical and interview data and groups to form the complex multiple choice questions. These have been formatted as an adaptive online test as described in the scheme below, in this case for the key concept of equilibrium. The final inventory will contain 6-8 such tests of key concepts

Question format

A complex multiple choice question format is being trialled for the test. This format has been used recently in the PISA testing (of 15-year-olds around the world) carried out under the auspices of the OECD (Cresswell & Vayssettes, 2006). Students respond individually with a true/false decision about each of the possible responses. This means that the test elicits more specific information about the students understanding.

A second design feature, which is built into most current concept inventories, is that the possible responses address the common alternative conceptions that students hold about the concept being tested. Ideally, these alternative conceptions have been identified in the science education research literature, but in many cases they exist in anecdotal form from teachers' comments.

Adaptive testing

One of the problems with concept inventories involves the choice of questions to make it a valid test for the widest possible range of students. There is always a compromise between the range of difficulty of the questions and the length of the test. Students starting an introductory molecular life sciences course may have a very different level of conceptual knowledge from a student completing such a course. A test covering both levels of conceptual understanding will leave the beginning student bewildered by the advanced questions and the completing student bored by questions that repeat lower levels of conceptual understanding.

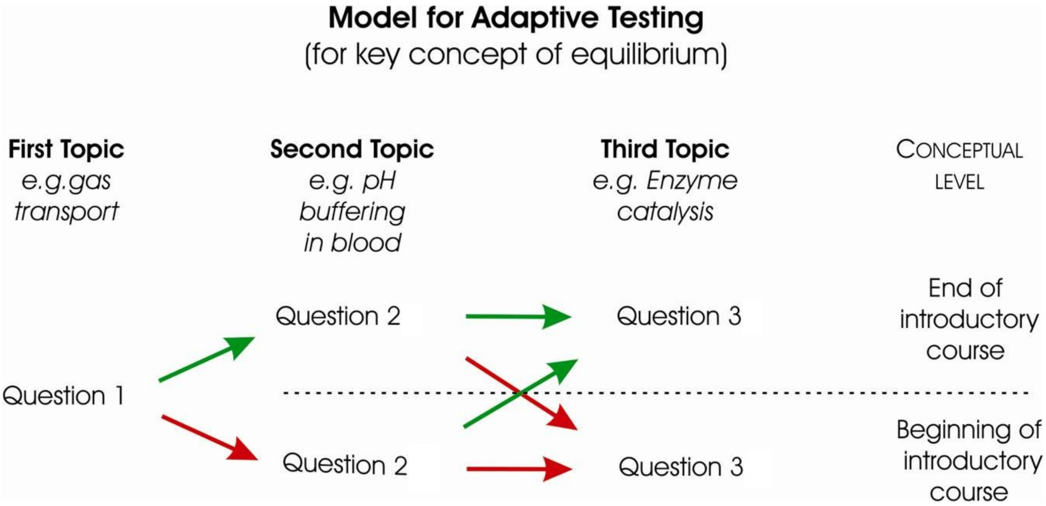


Figure 2. Adaptive testing scheme for the key concept of equilibrium. The pale arrows indicate the expected pathways for students at the end of their first biochemistry course. The dark arrows indicate the expected pathway for naïve students.

A solution to this problem is to use adaptive testing, in which the questions students are asked are dependent on the understanding they have demonstrated. In the case of the Molecular Life Sciences Concept Inventory, we are developing the test so that students attempt three questions on each concept and the second and third questions are adaptive and based on their response to the previous question (Figure 2). This approach requires that the test is administered on computer.

Preliminary Results

The trialling of the first question set has been completed with 209 students. The test contained 26 items, to which the students could choose a TRUE, FALSE or DON'T KNOW response. A factor analysis was carried out on the data to provide a clearer picture of the nature of the test and together with a multiple correspondence analysis, indicates that the test is examining a single broad concept, rather than discrete sub-concepts. The results based on student responses to all the questions gave an average of 60%, with the distribution shown in Figure 3.

The setting for the molecular life science inventory provides a different challenge from the chemistry inventory (Mulford & Robinson, 2002), in the sense that the concepts such as dynamic equilibrium are key concepts that are introduced in late high school and in introductory chemistry courses at tertiary level. Life science educators might assume their students have a working knowledge of the concepts. These preliminary results show that many students hold a very superficial understanding, able to recognise the terms, but not apply the concepts in the biological context. This is very useful information for the educator, because he or she can take care to reinforce the conceptual understanding and provide remedial assistance for those members of the class who need it.

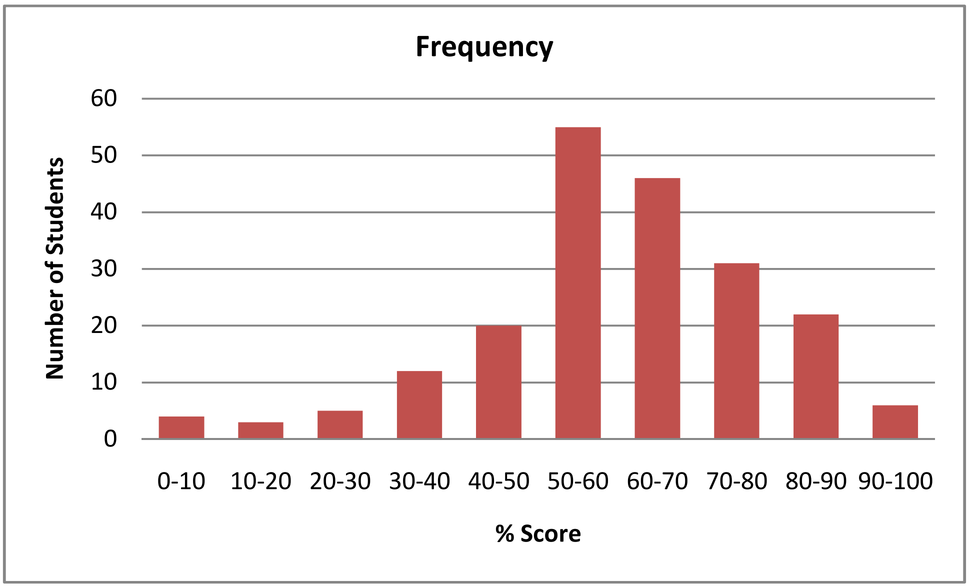
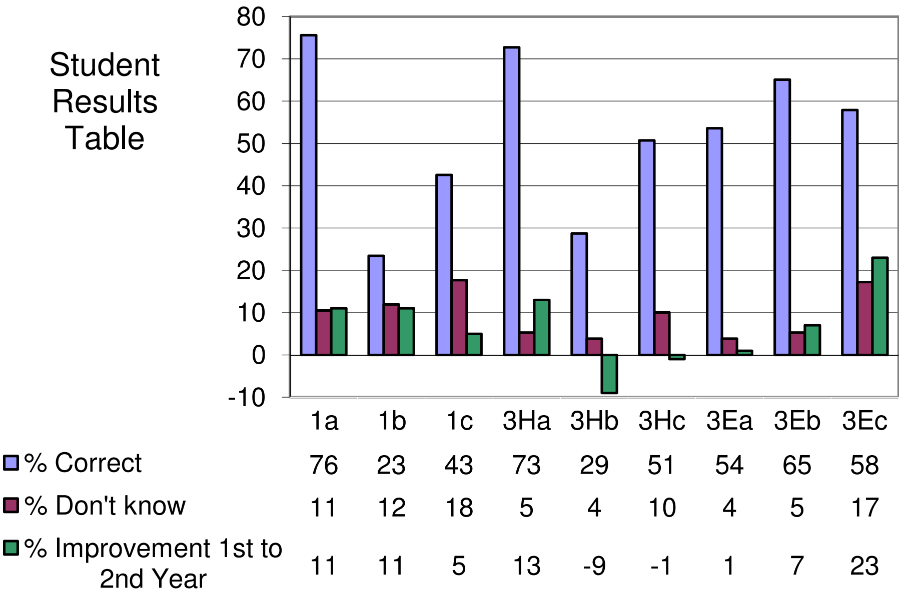


Figure 3: Student results on the trial 26 item test on equilibrium.

One of the major preliminary findings is that students correct responses, on average, increased, from first to second year, by about 10%. (Figure 4).



	1a	1b	1c	3Ha	3Hb	3Hc	3Ea	3Eb	3Ec
🟦 % Correct	76	23	43	73	29	51	54	65	58
🟥 % Don't know	11	12	18	5	4	10	4	5	17
🟩 % Improvement 1st to 2nd Year	11	11	5	13	-9	-1	1	7	23

Figure 4: Analysis of student responses to final list of 15 questions in the adaptive test, by student cohort.

Half the students were in their first semester of university study and hence, had not undertaken an introductory molecular life science course. The other half of the students who were in their second year of university had completed an introductory molecular life science course. While the 10% increase is disappointing at first sight, it is in line with results for concept inventories in other disciplines. For example, Mulford and Robinson (Mulford & Robinson, 2002) have reported a 5% increase in students scores on a chemistry concept inventory before and after taking a first year general chemistry course.

Item Analysis

The results have also been analysed for individual items to provide a basis for constructing the concept inventory. Item response theory (Baker & Seock-Ho, 2004) has been used to assign levels of difficulty to each of the items and a discrimination factor. This information has been combined with an analysis of the conceptual ideas addressed in the questions to select items for the inventory. In the case of the equilibrium concept, 12 items have been selected from the 26 items of the trial and three new items have been written to cover an aspect of equilibrium that was identified as missing in the trial.

The trial results also provide a glimpse of the detailed information that the concept inventory can give about student performance, as outlines below.

i. The items, which cover the same concept in the same context, can achieve very different success rates from students. Question one, for example, examines student understanding of an equilibrium process involved in oxygen storage in muscle.

Question 1.

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. (Correct answer given in brackets)

(a) Myoglobin binds oxygen (O_2) and is able to release it chemically unchanged. (true)

(b) Each oxygen molecule remains bound to a myoglobin molecule until it is needed. (false)

(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)

ii. Item (a) was answered correctly by 76% of students, while only 23% answered Item (b) correctly. Item (a) requires the student to understand the overall effect of the equilibrium process on the oxygen molecule, while Item (b) requires the student to picture the equilibrium as a dynamic process. The results show that three quarters of the students have a superficial grasp of the concept, but only one quarter of the students have the depth of understanding to visualise the dynamic process.

iii. The results also suggest that students are often unable to make the connection between the concept and the context. Thus the correlation between a student's success on the context of Question One with their success on Question Three (enzyme catalysis, see Figure 4) is at best modest. This reinforces the idea that students commonly have a superficial understanding of the concept that is strongly tied to the context, rather than a deep understanding that allows them to see the conceptual patterns of the discipline.

iv. The differing performance of first and second year students illustrates that teaching can undermine aspects of their understanding. Second year students were less successful answering Question 3Hb than first year students. A speculative reason for this surprising result is that first year students applied their chemistry knowledge (with modest success) and second year students may have been less successful because they had studied the topic in greater detail, but without appreciating the role of equilibrium.

v. Significant numbers of students fail to demonstrate even a superficial conceptual understanding on any particular item. (The highest success rate on any of the questions was 76%). However, they often have some success in other contexts. This means that educators who assume any level of prior conceptual understanding will be leaving these students behind.

Interview Data

Interviews were held with nine students, 4 commencing and 5 having almost completed their first biochemistry course. A sample of responses to Question 1 above on equilibrium illustrates the different range and quality of responses.

Some explanations for responses to Item (b) were as follows:

Student 1 (correct answer): "*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 equilibrium, it's like a constant process. That's how I thought about that one*."

Student 2 (incorrect answer): "*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 the oxygen concentration in the tissue.*"

Student 3 (correct answer): "*I changed my mind on this and I read it a second time. I originally thought it might be true because you know it looks after the oxygen until it's needed by the cell. And then I kind of changed my mind to false and thought it more in the sense that it's …a single oxygen molecule won't be bound to a single myoglobin molecule. There'll be kind of bound and unbound, bound and unbound until in a general sense all the oxygen is being used and then more will be bound than unbound. It's an equilibrium instead of being one at a time.*"

From these responses is may be concluded that Students 1 and 3 had a good working understanding of the dynamic nature of a chemical equilibrium. Student 3 showed that he was able to progress from his initial incorrect conclusion (in which he applied much the same reasoning as student (2) to the correct explanation.

Student 2 apparently visualised the process in static terms and relied for explanation on a recall of physiological "facts" rather than application of underlying chemical principles.
A number of students gave correct answers but with faulty reasoning. For example, one student rationalised his correct answer as follows"

"It can either go two ways… um ..either reactions are bound together because they like two components are bound together because they produce …um….reaction pathways. That's one purpose or they're separate so that when a reaction is needed it can …start, but yeah I said false, because oxygen's usually needed for other things other than myoglobin. So that's why I said that."

Throughout the interview, this student highlighted a difficulty in using scientific language to make a chemical argument. Interviews provided further support for the conclusions described above, in particular that students could not make a connection between the concept and the context, and that many lack even a superficial understanding of the concept.

Summary

The exercise of developing a concept inventory for the molecular life sciences is providing very useful insights into student learning in the disciplines. In part, this is because the act of identifying the concepts to be examined is forcing an examination of the conceptual structure of the material that is taught. This has led to the identification of a group of big ideas that provide an explicit conceptual framework. While this framework is but one of many possible ways of analysing the young disciplines that fall within the molecular life science banner, it is being developed to provide a coherent group from which educators will be able to draw. For the project, the group of big ideas has been used to identify a number of key concepts that will be examined in the inventory and it provides a basis for testing the utility of these concepts.

Question sets that address each of these key concepts are being developed and the process for this development has been trialled. This process has involved the linking of the educational research literature about students' conceptions to the curriculum, which has been built into questions as they are written, but also uncovers the wide gaps in the educational research on topics in the molecular life sciences.

The student results from the trial data have tentatively confirmed the results from concept inventories in other disciplines, namely, that students can succeed in courses, but fail to master conceptual ideas that underpin a deep understanding of the subjects. The data that will be available from the inventory will both inform the educator about likely student performance, and, when administered to their own classes, provide vital feedback for their teaching and for individual students about their learning.

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