Building, Using, and Maximizing the Impact of Concept Inventories in the Biological Sciences

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Abstract

Following the success of the Force Concept Inventory, there are now many simultaneous efforts to develop concept inventories in the biological sciences. Simultaneous development poses both a potential danger (that groups may develop competing, rather than complimentary instruments) as well as a tremendous opportunity (to organize and leverage current efforts in ways that provide complementary coverage). Given these considerations, a face-to-face meeting focused on organizing and leveraging current and planned efforts, was recently hosted by the Biology Concept Inventory Team with National Science Foundation support to address these and related issues. The meeting report below recounts the motivation behind the meeting, provides a short overview of CI's, and summarizes the larger issues and themes that span all projects (with a web-link to the full papers as well as participant biographies), a summary of meeting discussion and outcomes, as well as our anticipated next steps. The meeting itself provided an ideal venue for leveraging current research findings about student conceptual learning in the biological sciences and a means of ensuring that those working on concept inventory development in the biological sciences communicate a coherent and persuasive message to the rest of the community.

Introduction

For many years, we have faced both the public demand and our personal convictions about the need to improve student learning experiences in the biological sciences at the post-secondary level. While the particular demands (and often our own desire to make improvements) may vary, their content is generally in agreement in terms of several things. First, students need to learn material at a deeper level than rote memory and second, student learning assessments and course program evaluation should be improved, meaningful, and integrated into course structure. Essentially, we are asked to help students learn at the conceptual level so that they leave our courses knowing considerably more than how to list, define, and label correctly. For example, Bio 2010 asked us to teach in ways that address students' misconceptions (NRC, 2003). Misconceptions can be broken down into five basic categories 1) preconceived notions; 2) nonscientific beliefs; 3) conceptual misunderstandings; 4) vernacular misconceptions; and 5) factual misconceptions (e.g., Committee on Undergraduate Science Education, 1997). Research on addressing misconceptions in the sciences suggests that a new concept cannot be learned until the student is forced to confront the paradoxes, inconsistencies, and limitations of the mental model that already exists in the student's mind. Students persist in their erroneous beliefs because they often seem more reasonable and/or useful to them (e.g. Mayer, 1987; Schneps, 1994).

While there are particular teaching approaches that facilitate student learning because they address misconceptions, faculty must also have some reliable means of assessing student learning at the conceptual level, assessments that are fundamentally different from the way we assess for traditional, rote learning that we (and our students) are most familiar with. This is where instruments such as concept inventories (CIs) enter the picture because they are research-based instruments designed to measure student conceptual understanding in areas where students are known (through rigorous research) to hold *common* misconceptions of one of the five types listed above. (CIs focus on misconceptions that are wide-spread among students.) There are

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many ways to assess students' conceptual understanding (e.g., concept mapping, learning portfolios, oral exams, etc.). We focus here on CIs for a number of reasons, but primarily because the Physics community has demonstrated that a widely-adopted CI can successfully provide a compelling argument and catalyst for change in the way teaching and learning are both approached. Wide-spread adoption of even a single CI also encourages the adoption of other, alternative means of learning assessment and program evaluation.

Like any instrument, CIs can be very useful. At the same time, they can cause some confusion among both faculty and students because their format resembles a typical, multiple-choice *test*. Learning environments, like any social setting are characterized by many (often unarticulated) rules. For example, when our students enter a science course, they have already been socialized to believe that the subject matter is based entirely on facts that can be learned using rote techniques. Science, Technology, Engineering, and Mathematics (STEM) disciplines are still considered by most students to be "black and white" rather than innovative, creative, or in need of further exploration. Students are rarely exposed to opposing theories on a given subject and the content is typically treated as things we know or certainties. This characterization is one of the reasons that students often forget that all science actually begins with observation, rather than with experimentation. Students are rarely asked to explain things such as how an older theoretical model was developed based on the observations and information available at an earlier time, and is modified and/or discarded as new information becomes available and we find that the model no longer explains what is observed to happen. When we assess STEM knowledge, we tend to focus on whether or not they have selected the one correct answer in the midst of other clearly wrong responses. Students and faculty both come to know what a test "looks like" and what the expectations are for those taking them. Since CIs look like a typical multiple-choice test, students and faculty both find it difficult to accept that there are levels of knowledge represented in the inventory and that the distracters are not so much wrong, but rather that each one represents particular places where students commonly become "stuck" in their understanding – levels of understanding that they must move beyond in order to completely understand in order to make use of conceptual knowledge. This leads to common misconceptions about CIs and faculty and students both often believe that they are "trick" questions rather than questions with potential responses that help inform us about where a student is in terms of their level of conceptual understanding. It is often easier to explain to students what the purpose and format of the questions represent than it is to assist faculty in truly understanding them. CI's are characterized by the following:

- Resemble typical multiple-choice tests, BUT distracters are based on research findings indicating misconceptions commonly held by students
- Distracters diagnose or map a particular level of student conceptual understanding
- Each distracter reveals where student understanding has gone astray or become "stuck"
- Teachers and students use this information to address problem areas with appropriate teaching techniques (which have also been identified through research on learning and understanding)

Motivation: The relatively fragmented nature of conceptual landscape in the biological sciences is an issue that hampers the development of concept inventories capable of providing the same level of catalyst for educational reform seen in other STEM communities, most notably the Physics Education Research community. Over the past 10 years, a number of discussions, workshops, and meetings have occurred which include the topic of concept inventories in the biological sciences. However, the majority of these meetings have either focused on internal needs and uses (e.g, MIT's development of the Biology Concept Framework; see Khodor, Halme, & Walker, 2004) or on the broader context of educational reform (e.g., The National Academies Summer Institute on Undergraduate Education in Biology, 2003). The Faculty Institutes for Reforming Science Teaching (FIRST I and FIRST II; 1999-2005) also include a component on assessing student-centered learning and as part of those projects, Kathleen Fisher and the San Diego Group, held a working group session focused on the assessment of conceptual understanding in the biological sciences *per se*. At the same time, the overall project goals for these and other such initiatives were much broader: educational reform and the institutionalization of student-centered learning approaches in the biological and other sciences (e.g., the reports and work generated by the NSF/Johnson Foundation Workshop on Bringing Research on Learning to the Geosciences; July 8-10, 2002).

It is true that the usefulness of concept inventories in any discipline does not exist separate from the goal of enhancing student learning, STEM education reform, and the need for reliable means of tracking the success or failure of the implementation of more student-centered learning approaches. However, it is clear that, for the first time, there are now a number of groups who are focused on efforts to develop concept inventory instruments in the biological sciences. As a result, the National Science Foundation (NSF) elected to sponsor a meeting among those currently working on CIs in the biological sciences, hosted by the BCI development team at the University of Colorado, Boulder. The meeting was designed to leverage these efforts in ways that enable us to provide a set of instruments that complement rather than compete with one another and facilitate each group's ability to develop and cultivate cogent, persuasive means of communicating the value and appropriate uses of CIs to others who teach in the biological sciences.

Meeting Overview

While many STEM disciplines (e.g., physics and chemistry) are housed in a single department, it is not uncommon to find multiple departments of biological sciences at a single institution. When we pair this type of fragmentation with the lack of communication typical among specialist in any discipline, it becomes clear how pedagogically-focused research addressed by ecology and physiology is often unfamiliar to those working to improve teaching and learning in cell and molecular biology. Thus, a critical goal for this meeting was to ensure that all group members became closely aware of work associated with CI development being carried on by others in the biological sciences. In an effort to reach our primary meeting goal, each participant submitted a short paper prior to the meeting, and these papers can be downloaded from the BCI website with the authors' permission (www.bioliteracy.net). During the meeting, each participant or a group representative gave a short presentation summarizing their work in CI development, use, and/or dissemination. In addition, most group members had extensive experience with the challenges of introducing new pedagogical approaches to faculty members, including those that focus on students' conceptual understanding (see, e.g., the Teaching Issues and Experiments in Ecology (TIEE) website which offers both a wide variety of strategies for teaching particular concepts in ecology, but also offers a wide range of faculty development material that can be applied to any course content; http://tiee.ecoed.net/). While the meeting focused on CI development and related issues, no CI instrument exists in a vacuum and the process of sharing and relating experiences connected to faculty development and classroom implementation to the development process proved highly beneficial as well (e.g., this most recent phase of the FIRST project is focused on compiling a large database of assessment information that includes meta-data and which can be used for secondary research purposes as well; see the Ebert-May, Weber, Urban-Lurain, McFall, and Jones meeting paper).

While the papers themselves provide the most complete information about the range of topics and discussion covered at the meeting, a number of common themes, issues, and challenges emerged. First, it is very challenging to identify concepts that represent *commonly held* student misconceptions. Even in projects that began with the results of prior research (e.g., see the Elrod meeting paper), continued work toward incorporating those results into a CI instrument indicated that many of the areas identified as conceptual in nature were actually topics, or fact-based (meaning they are things that can be memorized by students effectively). While facts are critical to learning in any discipline, a CI instrument is not the appropriate way to assess fact-based student learning. Thus, an issue common among CI development projects is that "digging" past rote learning identify concepts is often difficult. This is a challenge seen at all levels of post-secondary education in the biological sciences (not just at the introductory level). The result of this difficulty is that it is easy for CIs to be constructed that cover more than commonly held student misconceptions in a particular area. When that happens, it lowers the validity and usefulness of the instrument *as a measure of conceptual understanding and learning*. In other words, if a student is able to use their knowledge of memorized vocabulary, processes, lists, and labels as a way to eliminate possible responses (if the instruments allow students to employ a test-taking strategy), it is not fulfilling the role of a CI. Fact-based and other types of knowledge simply need to be assessed in another way. This also means that there are fewer concepts in the biological sciences than the amount of course material typically covered.

Another issue that we face is our ability to communicate effectively about CIs. Most important is clarity about what those of us building CIs mean when we use the term "concept"; what others in the biological sciences believe we mean when we use that term; etc. Any lasting and important change in teaching and learning in the biological sciences in addition to assessment and program evaluation requires a strong and meaningful vocabulary to communicate the need for and reasonableness of change. In many ways, the term "concept" appears to have either become ubiquitous or remains too broad to be consistently meaningful both within our own community and as we reach out to others. A number of group members replaced the term "concept" with the phrase "big ideas". Thus, it may be more helpful when communicating both among those who focus on the idea of enhancing students' conceptual understanding and with those who are new to this area, to discuss our work in terms of identifying and finding ways to diagnose or inventory the "Big Ideas" in the biological sciences. This issue was raised in part because it is difficult to separate the notion of topics (which is how most post-secondary material is currently organized) from what we mean by concepts. One of the most challenging tasks any CI developer has is to explain to others who teach in the same area why it is that not all topic areas listed on the syllabus (for example) are represented in the content of the inventory. One portion of this difficulty comes from the fact that, while it seems easy to distinguish between rote memorization and higher levels of learning, there really is a great deal of any STEM discipline that requires a certain amount of learning vocabulary definitions (much of which can be memorized); the ability to correctly label (again, something that can be memorized); and lists (which can and are usually memorized). While these abilities and skills are absolutely essential to students' ability to progress in a discipline, they do not represent conceptual level understanding. Nor should they be assessed using CIs. So, when we talk about a vernacular misconception, it is not the same as not knowing the vocabulary definitions. For example, as recently as 15 years ago, students regularly confounded the portion of natural selection about survival of the "fittest" with survival of the "strongest" or, even more often, they assumed that "weakness" would fail to survive. This type of misconception does not appear in students' thinking until they are in later courses – courses that require them to apply what they understand about natural selection to a problem that they have not seen before. It also prevents them from moving beyond what we currently know about natural selection because it provides a deep-seeded "blinder" that keeps the student from looking at new information (or even current or old information) in new ways. Perhaps discussing the "Big Ideas" in the biological sciences (rather than 'identifying the concepts') addresses both the tendency of professors to "think" about their discipline in terms of topic areas (there are many more topics than there are concepts) and helps them to better understand the purpose and uses of CIs, particularly since CIs "look like" multiple choice tests, even though that is not what they are and is not how they are used.

Naturally, this issue is also closely related to some of the difficulties CI developers can encounter when they pursue dissemination and adoption: faculty can misunderstand the distinction between concepts and topics. The result can be that, when they examine the CI, they notice that many topic areas they cover in their course are not present and they may assume that the instrument is: a) incomplete and/or b) implying a value judgment – that they should skip topic areas that are not conceptual in nature. Electing to utilize a CI and to teach students in a way that focuses on concepts does not necessarily mean eliminating course content. CIs are simply one tool that can provide faculty with an overview of their particular students' strongest areas of conceptual understanding (so they can make choices about where to spend the majority of their class time based on actual student need). CIs can also provide a research-based pre- and post-instruction comparison that can be used to determine how well a new course intervention or regular teaching approach has worked. Although CI instruments most commonly use multiple-choice test formats that are based on word-problems, they can also ask students conceptually-oriented questions using pictorial representations or hierarchical structures. Perhaps the best known alternative to the multiple-choice format is the use of concept-mapping. Recent, technology-based concept maps can be used both as an automated assessment tool as well as a student learning tool. For example, some are using it to help students learn to make connections among processes (see the Luckie paper). When used this way, the focus is not on students' ability to fill in the major categories in, such as a process (something that can be learned by rote), but rather, student's ability to explain how those processes are connected to one another (a concept-level task).

Finally, we held a number of small group discussions designed to develop and facilitate future collaborations among attendees (and which are very briefly discussed here). One group discussed Introductory Biology courses and what the "Big Ideas" are at this level and came to agreement on some of them, such as the Laws of Biological Thermodynamics (conservation, energy, mass), self-regulating systems (beyond homeostasis; steady state systems; molecular), evolution and history. Group members discussed putting Intro Biology concepts into the framework proposed by one of the groups from Michigan State University (MSU) who participated in the meeting (see the meeting paper by Parker, Anderson, and Merrill), but spent more time focused on attempting to agree on a small and reasonable number of conceptual areas. Another group of those interested in further discussing the "Big Ideas" in Genetics elected to begin by applying the framework proposed by MSU as an organizing schema that we might all be able to use. These participants have since followed through with additional meetings and work in an effort to further organize the Genetics Concept Inventory in terms of the MSU framework. Those participants interested in the concepts surrounding the topic area of the Nature of Science (NoS), discussed NoS as a "Big Idea" and how one of the large, conceptual learning goals for any course in the biological sciences must be that students come away with an understanding of the nature of science. After they mapped out what they felt the Nature of Science would "look like" in terms of the biological sciences, they then continued to discuss and consider whether or not there should be a separate set of NoS questions that should be integrated into all CI instruments in the biological sciences. In the biological sciences, we face the challenge of teaching students about evolution, a conceptual area that is at odds with some students' ontological perspectives. A group interested in student understanding of concepts related to Evolution discussed the need to take into consideration cultural and other beliefs that may represent commonly held misconceptions and be used as distracters in CI questions. This is particularly tricky because it is unusual for science courses of any sort to treat and touch on ontology (or people's conception of reality). Science is generally taught based on the assumption of a particular ontology (reality is assumed to be a constant) and that it is students' epistemological beliefs (or their ways of coming to know or discover the truth) that might be at fault. Science generally fails to acknowledge any other ontological system. Finally, a number of previous and existing projects related to conceptual level learning and Ecology have long-standing track-records and a number of participants in our meeting represented or have participated in the past with those projects. This Ecology group elected to discuss broad, conceptual goals for students taking Ecology courses (this included giving consideration to whether or not there should be a set of nature of science questions included in ecology-focused CI instruments). They also looked at how the "Big Ideas" in ecology fit with the MSU framework.

Next Steps

The first meeting of a group of biologist and people working in STEM education research, concluded by planning our next steps. In addition to continuing to pursue further collaborations among group members and to continue our current work, we decided that continued progress in the area of building, using, and, maximizing our work to employ CI's as one means of improving student learning in the biological sciences depends upon holding at least one other face-to-face meeting before another year passes. To further this effort, Susan Elrod volunteered to organize and host our next meeting (within the next 9 months) and we set pre-meeting goals and a tentative goal. Prior to the meeting, in addition to continuing our own work as well as furthering collaborations, we decided that it would be critical for each of our groups to produce another pre-meeting paper. This paper will focus on clearly articulating 1) the "big ideas" that our own CI measures; 2) what our group believes a CI actually is (its goals, purpose(s), approach, etc.); 3) how our CI goes about measuring the "big ideas" we identified in goal 1; and 4) how the data collected and measured by our CI is and can be used to inform and improve teaching and learning. In addition, papers prepared for this next meeting will discuss the elements of our individual work that is ready for dissemination to the broader community of educators in the biological sciences. These pre-meeting papers will provide the foundation for the next meeting, the goal of which is to conduct a meta-cognitive analysis of the individual papers so that we can clearly articulate more about where we are in terms of the state of the art of development of CIs in the biological sciences and how these instruments can and will be used to improve student learning in the biological sciences (and, whenever possible already are being used for this purpose). These documents, along with the results of our next meeting, will enable us to communicate clearly how CIs connect with teaching and learning goals and the where materials that support concept-based learning that connects to particular CIs can be found.

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