Biology Concept Inventories: Overview, Status, and Next Steps

CHARLENE D'AVANZO

Faculty from numerous science disciplines have used concept inventories to focus their efforts on a few core concepts and ways of thinking in introductory courses. These inventories also help faculty recognize students' misconceptions and faulty reasoning from the onset of a course and track gains in understanding as the course progresses. The biology concept inventories that several groups of biologists and educators are now working on will add significantly to the few that have already been published. This article introduces biology faculty to concept inventories, including what they are and how they are developed and used. In addition, I propose next steps, which would lead to faculty development workshops based on the use of concept inventories, student-active teaching, and scientific teaching in introductory biology courses. These workshops could be offered through professional biological societies and coordinated by societies' educators working together on common goals and strategies.

Keywords: biology concept inventory, scientific teaching, faculty development, introductory biology, biology concepts

Biology students' failure to understand core biological concepts—a focus of many reports on biology teaching reform (e.g., NRC 2003)—has stimulated several teams of faculty and educators to begin developing concept inventories in biology for use in college-level courses (table 1). As the physics Force Concept Inventory (FCI) does (Hestenes et al. 1992), biology inventories have the potential to help faculty pare the sheer volume of information they cover by allowing them to focus on fundamental comprehension of core ideas and thinking. For physicists, using the FCI along with interactive engagement methods based on constructivism, peer instruction, and ongoing feedback proved to be especially effective in fostering student learning of mechanics (Hake 1998). Learning physics is quite different from learning biology (Klymkowsky et al. 2003), of course, but undergraduate biology teaching too could benefit from a set of concept inventories that faculty could choose from and use. This article will introduce biology faculty to concept inventories, explaining what they are and how they are developed, in the hope that informed faculty will recognize and seize opportunities to participate in activities such as the workshops described at the conclusion of the article.

Concept inventories are research-based instruments that measure students' conceptual understanding of topics for which students share common alternative conceptions (also called "misconceptions") and faulty reasoning (table 2). A good concept inventory can therefore inform faculty of the likelihood that a student does not understand a core concept or idea, as well as indicate which mental constructs the student is holding onto (Klymkowsky and Garvin-Doxas 2008). Best known is the FCI, which consists of 30 multiple-choice questions about Newtonian mechanics and is widely used in physics education (Halloun and Hestenes 1985, Hestenes et al. 1992). For physics experts, the answers are obvious, but novices in introductory courses score poorly because incorrect responses intentionally match common misunderstandings. The surprise that even the best students do poorly has been a wake-up call for many physics teachers, including Eric Mazur at Harvard, who clearly recognized the core problem and necessary response: "How could these undoubtedly bright students, capable of solving complicated problems, fail on these ostensibly 'simple' questions? Slowly the problem revealed itself; many students concentrate on learning recipes...without being attentive to the underlying concepts.... A first step in remedying this situation is to expose the problem in one's own class. The key, I believe, is to ask simple questions that focus on single concepts" (Mazur 1992).

Since publication of the FCI, inventories have been developed in numerous scientific disciplines, including chemistry (Landis et al. 2001) and geology (Libarkin and Anderson 2006).

Charlene D'Avanzo (e-mail: cdavanzo@hampshire.edu) is a professor of ecology and the director of the Center for Teaching and Learning at Hampshire College in Amherst, Massachusetts. Her primary interest is science faculty development.

Table 1. Biological concept inventories and other diagnostic tests for use in college biology courses.

Diagnostic inventories	Status	Reference
Inventories validated by research		
Concept inventory of natural selection	Published	Anderson et al. 2002
Biology concept inventory	Published (online)	Klymkowsky and Garvin-Doxas 2008; *www.bioliteracy.net*
Diagnostic Question Cluster: Matter and energy	Under development	Wilson et al. 2006
Diagnostic Question Cluster: Genetics	Under development	Parker et al. 2008; *http://bioliteracy.net/CABS.html*
Cell division diagnostic test	Stable (see reference), unpublished	Williams et al. 2008; *http://bioliteracy.net/CABS.html*
Natural selection diagnostic test	Stable (see reference), unpublished	Williams et al. 2008; *http://bioliteracy.net/CABS.html*
Osmosis and diffusion diagnostic test	Stable (see reference), unpublished	Williams et al. 2008: *http://bioliteracy.net/CABS.html*
Other diagnostic tests		
Osmosis and diffusion diagnostic test	Published	Odom and Barrow 1995
Natural selection instrument	Published	Nehm and Reilly 2007
Genetics concept inventory	Under development	Elrod 2008; *http://bioliteracy.net/CABS.html*
Diagnostics tests on energy and matter and the nature of biology	Under development	Williams et al. 2008; *http://bioliteracy.net/CABS.html*

Note: Validation is a research process that includes in-depth student interviews to establish misses (misconceptions and faulty thinking not identified) and false positives (student does not hold the misconception). "Other diagnostic tests" here refers to sets of questions that have not undergone this particular process; they have, however, been studied through analysis of pre- or posttests, for instance.

Different from most multiple-choice tests

Concept inventories are multiple-choice tests that can be scored objectively, a critical strength. However, they differ from typical multiple-choice tests in several important ways (Garvin-Doxas et al. 2007). The wrong answers, called "distracters," (a) are based on extensive research, (b) are in students' own words, (c) diagnose a specific level of student conceptual understanding, and (d) clearly reveal where students are getting stuck. Since distracters are known to be incorrect answers that many students will choose, faculty expect that most entry-level students will do poorly on a well-researched inventory used as a pretest. Distracter answers in concept inventories are developed through extensive research that often includes interviews with students to get at their rationale for specific responses and analyses of written, open-ended answers to questions (Richardson 2005). Such extensive psychometric research is called "validation." Careful examination of students' responses helps researchers better understand why students may believe, for example, that nature is inherently in balance or that plants obtain carbon from the soil (table 2).

Sadler (1998) explains how development of distracter-driven multiple-choice tests allows researchers to combine the power of both qualitative research and quantitative assessment to measure change in students' concepts of carefully defined phenomena. Education researchers regard interviews with students as qualitative because they often rely on one-to-one interactions and on interpretations of student responses; moreover, the numbers of students interviewed are usually small. Nonetheless, interviews have proved to be an extremely

Table 2. Some common misconceptions held by students in undergraduate biology courses.

Field of biology	Misconception	Reference
Ecology	Nature is inherently stable.	D'Avanzo 2003
	Species coexist because they need to get along.	Stamp and Armstrong 2005
Evolution	Changes in traits are need driven and mutations are intentional; therefore randomness is not recognized as important.	Anderson et al. 2002, Klymkowsky et al. 2003, Williams et al. 2008
	All members of a population are nearly identical.	Anderson et al. 2002, Williams et al. 2008
Physiology/metabolism	Plants get carbon from soil.	Anderson et al. 1990
	Both matter and energy are physical substances.	Hogan and Weathers 2003
	The human body can "run out" of oxygen.	Michael et al. 1999

Note: Examples represent coherent patterns of alternative thinking as opposed to isolated misunderstandings (Chi 2005). A misconception, also called an "alternative conception," is a naive explanation shared by many students very resistant to instruction (e.g., D'Avanzo 2003). Sources and reasons for such alternative conceptions are many; they include diagrams in books, personal experience, and lack of knowledge about basic scientific ideas.

valuable way to display students' mental models and the reasoning behind students' answers (e.g., Duckworth 1987). In contrast, multiple-choice tests can be given to very large numbers of students, which increases their reliability, and well-conceived questions can show how many student responses match those of experts (Dufresne et al. 1992), for example.

Development of biology concept inventories

For many biologists, the term "concept inventory" is problematic because it implies that we share a set of agreed-upon concepts for introductory biology classes, as physicists do for mechanics. But papers from several meetings on Conceptual Assessment in Biology (CAB; Garvin-Doxas et al. 2007) demonstrate that this is certainly not the case. One reason biologists disagree about essential biology concepts or ways of thinking for beginning college students is that these faculty are a disparate group who teach a broad range of introductory courses. They may be physiologists, geneticists, or ecologists teaching courses for one or two semesters—for majors, nonmajors, or both—to 400 students or 15, and they may cover the classic topics (evolution, genetics, metabolism, ecology, etc.) or focus more on single subjects and scientific inquiry. As a result, biologists argue about which "big ideas" are most important or what nonmajors need most, among other issues (box 1).

Faculty development workshops and concept inventories

Despite these challenges, several teams of biology educators and teachers are focusing their efforts on developing concept inventories, and therefore college faculty will soon have available a diverse and growing set of such inventories and related diagnostics (table 1). In addition to the first validated inventory—the Conceptual Inventory of Natural Selection developed by Dianne Anderson for her doctoral thesis (Anderson et al. 2002)—is the Biology Concept Inventory, which focuses on random processes in biological systems (Klymkowski and Garvin-Doxas 2008) and diagnostic tests for natural selection, cell division, and osmosis and diffusion (Williams et al. 2008). Also validated are sets of Diagnostic Question Clusters (DQCs) for cellular respiration and for genetics (Wilson et al. 2006, Parker et al. 2008). And other diagnostics in genetics and osmosis/diffusion (table 1) have been prepared. Given this set of instruments and others that are likely to come, how will biology faculty know which inventories would be most effective for their situation, and how do they learn to use them? Presented below are ideas for faculty development workshops on the use of concept inventories, plus student-active approaches and scientific teaching, that would help faculty with this process.

Million-dollar instruments. For those unfamiliar with concept inventories, the best way to appreciate these diagnostics' value and purpose is to learn how such inventories are developed. One key consideration is the composition of the groups working on concept inventories; biology teams can include faculty actively teaching general biology and education researchers trained in psychometics, science epistemology, scientific literacy, or patterns of scientific reasoning, for example. This composition illustrates the range of expertise and experience needed to construct concept inventories with the potential to reform science teaching. Another critical factor is the length of time required for this type of research—a decade or more in some cases. Concept inventory questions are therefore called "million-dollar instruments" (Isidoros Doxas, Tech-X Corporation, Boulder, Colorado, personal communication, 24 June 2008) because the time and skill required to create them is so great.

I will use the work of Joyce Parker, Andy Anderson, John Merrill, and others at Michigan State University as a specific example of the development of inventory questions. These researchers know the landscape of poor student reasoning in introductory biology courses because they have been working on this issue for many years (e.g., Anderson et al. 1990). On the basis of this experience, the team begins by asking students open-ended questions about important ideas in biology that they know are problematic for students (Wilson et al. 2006). These students' incorrect answers then become distracters for multiple-choice questions. To assess whether researchers accurately understand why students are selecting distracter questions, they next ask students to explain their reasoning for specific answers in interviews and in extended written answers. Confidence in the reliability of a question grows when student responses are consistent on subsequent multiple-choice tests (Sadler 1998).

Wilson and colleagues (2006) identify the instruments they are developing as sets of diagnostic questions (DQCs) rather than concept inventories. This distinction highlights their emphasis on faulty patterns in student thinking that could span a biology course (box 2); thus, students' conceptions about one process in biology would be linked to beliefs

Box 1. Why biology faculty find it difficult to decide and focus on a limited set of concepts for introductory biology courses.

Faculty are trained in a wide range of biological disciplines and therefore disagree about what concepts and ideas are most important.

Faculty expect students to be prepared for any upper-level courses they teach.

Introductory biology is a terminal science course for many students; faculty disagree about what is most important for them.

Textbook coverage is very large, and students expect faculty to present this information.

Premed students in particular demand coverage.

Many faculty teach courses like the ones they took.

Greatly changing a course takes a good deal of time.

Box 2. Diagnostic Question Clusters identify problematic patterns in student thinking about challenging biology content.

Jared, the Subway man, lost a lot of weight eating a low-calorie diet. Where did all the fat/mass go?

a. The mass was released as CO_2 and H_2O.

b. The mass was converted to energy and used up.

c. The mass was converted to ATP molecules.

d. The mass was broken down to amino acids and eliminated from the body.

Note: The correct answer is in bold. Distracters for the "Jared question" show that students confuse matter and energy, thinking about them interchangeably. Teachers who are aware that students may use this thinking when they study cells, organisms, and ecosystems can explicitly address this in their course design—and use DQCs (Diagnostic Question Clusters) to track their students' thinking as the course progresses (Wilson et al. 2006). Thus faculty can use these related sets of questions (clusters) to recognize and follow students' faulty reasoning across a course.

about related processes and to their overall understanding of how biologists think about biological questions and phenomena. Similarly, the Biology Concept Inventory developed by Mike Klymkowsky and colleagues at the University of Colorado, Boulder, emphasizes randomness, process, and structure (Klymkowsky and Garvin-Doxas 2008), which are basic constructs for nearly all biological topics taught in a general biology course. Inventory questions like these will be a great benefit for faculty who urgently need higher-level thinking exam questions.

Using concept inventories with active learning and a scientific teaching approach. According to David Hestenes, developer of the FCI, the good news about using this inventory is that students' scores particularly improve in courses that emphasize active learning; however, the bad news is this kind of teaching is not easy for physics faculty to do (Hestenes 1998). Similarly, biology faculty will need a good deal of help integrating use of a concept inventory with student-active teaching methods (D'Avanzo 2007). What we are asking biology faculty to do—select the appropriate inventory for their class, give the inventory as pre- and posttests, and interpret the results, as well as use interactive teaching methods to reinforce student understanding—will be challenging for even the most experienced teachers. To address this challenge we will need a faculty development approach that explicitly incorporates the use of concept inventories with student-active methods such as cooperative group work, concept maps and other visualization tools (e.g., Baum et al. 2005), and formative evaluation (D'Avanzo and McNeal 1997, Udovic et al. 2002, D'Avanzo 2003). Nehm and Reilly (2007) showed the value of pairing a natural selection misconception survey with active teaching in college biology courses; their research also highlights misconceptions unaltered by student-active activities, which is critical information for planners of faculty development workshops.

In addition to using concept inventories along with active teaching, a scientific teaching model would be a valuable foundation for this faculty development program. Scientific teachers apply their training and experience as researchers to their instruction. Although the central arguments embodied in the idea of scientific teaching are not new (Boyer 1990), the *Science* article by Handelsman and colleagues (2004) explaining scientific teaching has been especially effective in capturing the attention of science faculty and educators. (Google Scholar lists more than 100 citations since 2004.) This is partly because the article's venue is a premier science journal, and also because this team of educator-scientists clearly and succinctly present the case for teaching "that mirrors science at its best—experimental, rigorous, and based on evidence." Also important is the idea that working with data on their students' learning has appeal to scientists.

Next steps: Biology professional societies coordinate efforts and expertise

As noted above, introductory biology courses are taught by faculty in all subdisciplines of biology. Therefore, widespread faculty development programs focusing on concept inventories along with student-active and scientific teaching could effectively be offered and coordinated through biological professional societies (e.g., America Society of Cell Biology, American Physiological Society, Ecological Society of America). These societies offer mechanisms for disseminating pedagogical materials (such as Web sites and publications), training opportunities for faculty (workshops at meetings), access to funding, and most important, the combined experience of many skilled and dedicated biology educators. I envisage, for example, a set of workshops and supporting efforts focusing on the use of inventories and student-active and scientific teaching given at professional meetings by teams of experienced biology educators with common training and vision. At the outset, representatives from teams would need to work together to set goals and strategies for meeting them. Some of these are listed below.

Goal: Identify what faculty will need. Faculty will need the following:

Useful, validated concept inventory questions that faculty trust. Questions must be readily available and must clearly match material taught in most introductory biology classes, and they should be flexibly organized to suit faculty's interests and needs. Also, faculty must be able to trust the utility and reliability of these questions.

Frameworks that organize big, overarching themes students do not recognize. A frequent complaint about general biology courses is the list of unconnected ideas students memorize but do not connect together. Frameworks identify "big ideas" (Wilson et al. 2006). These are organizing principles spanning a course—linchpin concepts—that research identifies as especially problematic for students; such ideas include energetics across subcellular to ecosystem levels of organization (box 2) and homeostasis (Michael 1998). These frameworks are critical to the use of concept inventories because with them faculty can see how inventory questions track understanding of big ideas throughout a course.

Help in integrating active teaching, scientific teaching, and concept inventories. Concept inventory questions are tools that help faculty recognize students' conceptual weaknesses. This recognition can lead to use of targeted active learning strategies designed to help students improve their reasoning and effectively learn basic biological ideas. Faculty can then assess gains in understanding and knowledge by examining student responses on one-minute papers, concept maps, and other types of formative feedback. Faculty will need a good deal of support incorporating these steps into their courses; for many, ongoing assistance will be necessary.

Short-term strategy. Establish initial mechanisms within professional societies for meeting faculty needs, such as the following:

Identifying and vetting inventory questions: faculty are more likely to pay attention to concept inventories deemed useful and valid by education leaders within their own professional societies. To start, questions could be discipline specific (e.g., focusing on genetics or cell biology) and therefore more motivating to faculty in that society.

Writing a white paper on effective ways to improve college science faculty teaching. A growing literature on faculty development and barriers to change (e.g., Akerlind 2007) will provide valuable guidance for the design of faculty development programs.

Box 3. Workshops for biology faculty focusing on student-active and scientific teaching: Some faculty testimonies.

Biology educators are offering programs to help faculty incorporate active teaching, formative evaluation, and a scientific teaching model in their classes. Three recent projects, including faculty testimonies, are briefly described here. Common program components include an initial workshop, faculty working in teams, and follow-up interactions. Evidence for the effectiveness of projects such as these will include long-term monitoring of student learning and enduring change in faculty teaching.

National Academies Summer Institute on Undergraduate Education in Biology. Week-long summer institutes targeting large classes at research institutions help faculty apply research on learning to students' retention of core concepts (Wood and Handelsman 2004, Musante 2005). The workshops are organized by a National Research Council committee. Program evaluation is under way, but fellows' testimonies (below) describe the workshop as an intense, transformative experience (Wood and Handelsman 2004). Ongoing interaction between team members was also important (Musante 2005).

> "I haven't felt the same excitement since I went to my first research conference."

> "This will change my approach to teaching and my professional career!"

American Society of Microbiology Research Residency. This program helps faculty experienced with active teaching pedagogy design evidenced-based, publishable research on their teaching. It begins with a four-day workshop followed by ongoing, electronic interactions. The program is organized by the American Society for Microbiology (*www.biology scholars.org*).

> "I found this experience to be a landmark experience in my teaching. [It] challenged my perspective as an experienced teacher."

> "I can never look at how my students learn or how I facilitate that learning in the same way again. I now have a more critical eye about the process of teaching and what I am measuring."

***TIEE* Research Practitioner Project.** The project began with a summer workshop for experienced faculty teams using scientific teaching to study common interests (e.g., students' quantitative thinking skills). During the semester, teams communicated through electronic discussions. Next, faculty worked together to present their findings at a meeting of the Ecological Society of America (ESA) and, finally, to publish research papers in *Teaching Issues and Experiments in Ecology* (*TIEE*), a peer-reviewed, electronic publication of the ESA (*www.tiee.ecoed.net*; D'Avanzo and Morris 2008). Publication of teaching scholarship was a core program goal, which faculty commented on:

> "It was not until the call for participants for the...project that I thought about doing research on my own teaching. I enjoyed the sense of shared mission.... [It was important to be] held accountable to see this through" (Bramble and Workman 2007).

> "Now that I can verbalize these ideas [after writing about them], I can use and communicate them to students as well as colleagues.... In short, before I wrote,...student-active concepts were in my head. Now Ican better apply these student-active concepts and improve my teaching strategies…" (Griffith 2007).

Offering pilot workshops. Piloting project components, such as workshops, will help program leaders address critical questions. What features characterize effective workshops and follow-up sessions? How much scaffolding do faculty need as they teach their courses? How should materials be organized on Web sites? How do faculty in different institutional settings use these materials? Box 3 gives examples of workshops that have introduced scientific teaching to biology faculty; workshops such as these can serve as models.

Building a cadre of workshop and planning leaders. Early workshop participants can be faculty already experienced with active teaching and formative evaluation. They can then help design and lead future workshops and other project components (e.g., electronic interactions, sessions at meetings).

Long-term strategy. A course of action is necessary to address the following:

Funding and oversight of large-scale faculty development programs. A nationwide, enduring faculty development program targeting introductory biology education will be expensive, with many components. Developers of this large-scale project will need vision and expertise in financing and managing complex education endeavors.

Challenges and issues at different colleges and universities. Introductory courses exist within the context of particular colleges and universities. The many quite different institution-specific challenges and issues make far-reaching changes in biology teaching very difficult. For instance, introductory courses at Research-1 universities may be taught by instructors hired for this purpose who may not frequent attend biology societies' meetings of a biology society. Reaching them may require other approaches. As another example, engaging in professional development programs such as those described here will "count" in tenure decisions at some institutions but not at others; new faculty must clearly understand the reward system in their schools. An oversight committee with faculty representing a broad range of institutions will help identify these differences.

Biology textbooks. Most discussions about improving general biology teaching eventually arrive at the same vexing problem: most biology textbooks are encyclopedias of information that reinforce content-based rather than concept-based teaching. For example, the general biology text by Campbell and Reese (2008), publicized as being used in two out of three general biology courses, has more than 1300 pages—not including the unnumbered index, appendices, and glossary. The pedagogy described in this article is better supported by concise textbooks that focus on a limited set of ideas and approaches integrated throughout the book. A planning committee composed of leaders from large professional societies of biologists could be instrumental in helping publishers move in this direction. Some publishers (e.g., Lange 2008) are seeking such advice.

Final thought

The Biology Education Summit, hosted by the American Institute of Biological Sciences, brought members of many biological associations together in May 2008 to discuss challenges in undergraduate biology education. The meeting focused on the types of professional development programs that biology faculty need, and on how biology organizations can work together to meet pressing challenges in biology education (*www. aibs.org/special-symposia/aibs_biology_education_summit. html*). In coming years this meeting may well be credited with stimulating the types of cross-organization cooperation called for in this article.

Acknowledgments

Gordon Uno and Andy Anderson looked at draft versions of this article. I also thank three anonymous reviewers for very helpful suggestions. This work is informed by National Science Foundation Division of Undergraduate Education grants 9952347, 0127388, and 0736943.

References cited

Akerlind A. 2007. Constraints on academics' potential for developing as a teacher. Studies in Higher Education 32: 21–37.

Anderson CW, Sheldon TH, Dubay J. 1990. The effects of instruction on college nonmajors' conceptions of respiration and photosynthesis. Journal of Research in Science Teaching 27: 761–776.

Anderson DL, Fisher KM, Norman GJ. 2002. Development and evaluation of the Conceptual Inventory of Natural Selection. Journal of Research in Science Teaching 39: 952–978.

Baum DA, Smith SD, Donovan SSS. 2005. The tree-thinking challenges. Science 310: 979–980.

Boyer EL. 1990. Scholarship Reconsidered: Priorities of the Professoriate. Princeton (NJ): Princeton University Press.

Bramble J, Workman M. 2007. Data-rich case studies improve students' abilities to interpret graphs in a large non-majors course. Teaching Issues and Experiments in Ecology 5: Research #1. (17 October 2008; *http://tiee.ecoed.net/vol/v5/research/bramble/abstract.html*)

Campbell NA, Reece JB. 2008. Biology. 8th ed. San Francisco: Benjamin Cummings.

Chi MTH. 2005. Commonsense conceptions of emergent processes: Why some misconceptions are robust. Journal of the Learning Sciences 14: 161–199.

D'Avanzo C. 2003. Research on learning: Potential for improving college science teaching. Frontiers for Ecology and the Environment 1: 533–540.

———. 2007. Changing teaching practice: Much more than a diagnostic test. Paper presented at the Conceptual Assessment in Biology Conference I; 3–4 March, Boulder, Colorado. (25 September 2008; *http://bioliteracy.net/CABS.html*)

D'Avanzo C, McNeal A. 1997. Research for all students: Structuring investigations into first year courses. Pages 279–300 in McNeal A, D'Avanzo C, eds. Student-active Science: Models of Innovation in College Science Teaching. New York: Saunders College Publishing.

D'Avanzo C, Morris D. 2008. Investigating your own teaching: Faculty as research practitioners. Academe 94: 40–44.

Duckworth E. 1987. The Having of Wonderful Ideas and Other Essays on Teaching and Learning. New York: Teachers College Press.

Dufresne R, Gerace WJ, Hardimen PT, Mestre JP. 1992. Constraining novices to perform expert-like problem analyses: Effects on schema acquisition. Journal of Learning Science 2: 307–331.

Elrod S. 2008. Genetics concept inventory (GenCI) development. 2008. Paper presented at Conceptual Assessment in Biology Conference II; 3–8 January, Asilomar, California. (25 September 2008; *http://bioliteracy.net/CABS.html*)

Garvin-Doxas K, Klymkowsky M, Elrod S. 2007. Building, using, and maximizing the impact of concept inventories in the biological sciences: Report on a National Science Foundation–sponsored conference on the construction of concept inventories in the biological sciences. Life Science Education 6: 277–282.

Griffith AB. 2007. Semester-long engagement in science inquiry improves students' understanding of experimental design. Teaching Issues and Experiments in Ecology 5: Research #2. (25 September 2008; *http://tiee.ecoed.net/vol/v5/research/griffith/abstract.html*)

Hake RR. 1998. Interactive-engagement versus traditional methods: A six-thousand student survey of mechanics test data evaluation of active learning laboratory and lecture curricula for introductory physics courses. American Journal of Physics 66: 64–74.

Halloun I, Hestenes D. 1985. The initial knowledge state of college physics students. American Journal of Physics 53: 1043.

Handelsman J, et al. 2004. Scientific teaching. Science 304: 521–522.

Hestenes D. 1998. Who needs physics education research!? American Journal of Physics 66: 465–467.

Hestenes D, Wells M, Swackhamer G. 1992. Force Concept Inventory. Physics Teacher 30: 141–158

Hogan K, Weathers KC. 2003. Psychological and ecological perspectives on the development of systems thinking. Pages 233–260 in Berkowitz A, ed. Understanding Urban Ecosystems: A New Frontier for Science and Education. New York: Springer.

Klymkowsky MW, Garvin-Doxas K. 2008. Recognizing students' misconceptions through Ed's Tools and the Biology Concept Inventory. PloS Biology 6: e3. doi:10.1371/journal.pbio.0060003

Klymkowsky MW, Garvin-Doxas K, Zeilik M. 2003. Bioliteracy and teaching efficacy: What biologists can learn from physicists. Cell Biology Education 2: 155–161.

Landis CR, et al. 2001. Chemistry ConcepTests: A Pathway to Interactive Classrooms. Upper Saddle River (NJ): Prentice Hall.

Lange M. 2008. The education publishing transformation. Presentation at the AIBS Biology Education Summit; 16 May, Washington, DC. (25 September 2008; *www.aibs.org/special-symposia/resources/Michael_Lange_Presentation.pdf*)

Libarkin JC, Anderson SW. 2006. The geoscience concept inventory: Application of Rasch analysis to concept inventory development in higher education. Pages 45–73 in Liu X, Boone WJ, eds. Applications of Rasch Measurement in Science Education. Maple Grove (MN): JAM Press.

Mazur E. 1992. Qualitative vs. quantitative reasoning: Are we teaching the right thing? Optics and Photonics News 3: 28.

Michael JA. 1998. Students' misconceptions about perceived physiological responses. Advances in Physiological Education 19: 90–98.

Michael JA, et al. 1999. Understanding students' misconceptions about respiratory physiology. Advances in Physiological Education 22: S127–S135.

Musante S. 2005. Creating a community of educators to improve undergraduate biology student learning. BioScience 55: 309.

[NRC] National Research Council. 2003. BIO 2010: Transforming Undergraduate Education for Future Research Biologists. Washington, DC: National Academies Press.

Nehm RH, Reilly L. 2007. Biology majors' knowledge and misconceptions of natural selection. BioScience 57: 263–272.

Odom AL, Barrow LH. 1995. Development and application of a two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. Journal of Research in Science Teaching 32: 45–61.

Parker J, et al. 2008. Frameworks for reasoning and assessment in Mendelian genetics. Paper presented at Conceptual Assessment in Biology Conference II; 3–8 January, Asilomar, California. (25 September 2008; *http://bioliteracy.net/CABS.html*)

Richardson J. 2005. Concept inventories: Tools for uncovering STEM students' misconceptions. Pages 19–25 in Invention and Impact: Building Excellence in Undergraduate Science, Technology, Engineering and Mathematics (STEM) Education. Washington (DC): American Association for the Advancement of Science.

Sadler PM. 1998. Psychometric models of student conceptions in science: Reconciling qualitative studies and distracter-driven assessment instruments. Journal of Research in Science Teaching 35: 265–296.

Stamp N, Armstrong M. 2005. Using "the power of story" to overcome ecological misconceptions and build sophisticated understanding. Bulletin of the Ecological Society of America 86: 177–183.

Udovic D, Morris D, Dickman A, Postlethwait J, Wetherwax P. 2002. Workshop biology: Demonstrating the effectiveness of active learning in an introductory biology course. BioScience 52: 272–281.

Williams, K, Fisher K, Anderson D. 2008. Using diagnostic test items to assess conceptual understanding of basic biology ideas: A plan for programmatic assessment. Paper presented at the Conceptual Assessment in Biology Conference II; 3–8 January, Asilomar, California. (25 September 2008; *http://bioliteracy.net/CABS.html*)

Wilson CD, Anderson CW, Heidemann M, Merrill JE, Merritt BW, Richmond G, Silbey DF, Parker JM. 2006. Assessing students' ability to trace matter in dynamic systems in cell biology. Life Sciences Education 5: 323–331.

Wood WB, Handelsman J. 2004. Meeting report: The 2004 National Academies Summer Institute on Undergraduate Education in Biology. Cell Biology Education 3: 215–21.

doi:10.1641/B581111
Include this information when citing this material.