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INNOVATIONS IN UNDERGRADUATE BIOLOGY TEACHING AND WHY WE NEED THEM

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Defining the challenge

Two principal forces are generating momentum for a revolution in the way biology and other sciences are taught in high schools, colleges, and universities (DeHaan 2005). First, there are deep concerns about our international competitiveness, amid indications that the U.S. is doing a relatively poor job at retaining and training students in the science, technology, engineering, and mathematics (STEM) disciplines (Glenn 2000, NAS 2004). Too many talented students, who get the impression from introductory courses that science is simply a collection of facts to be memorized, are dropping out of STEM majors (Seymour & Hewitt 1997) with little understanding or appreciation of what science is all about. For students that do major in life sciences, there is concern that future research biologists are being inadequately trained (Stryer 2003).

The second driving force for reform is recent research from educators and cognitive scientists on how students learn. This research has provided strong evidence that the traditional teaching methods employed in most secondary-school and undergraduate introductory courses are far from optimal for promoting student learning. Alternative research-based methods have been developed and shown to be more effective, and a growing number of STEM faculty and administrators aware of these methods are pushing for their adoption.

Beyond the general findings about how people learn, there is now a substantial body of discipline-based educational research (DBER), dealing with teaching and learning of specific STEM disciplines. This review will refer to some of the more important general findings on how students learn, but will primarily highlight results and applications from recent DBER and, more specifically, life sciences education research (LSER). It will focus on teaching and learning for undergraduates, particularly in large courses, where innovation is most needed.

History and current state of DBER

DBER grew out of the efforts of physicists in the mid-1980's, who discovered that most undergraduate students in their introductory courses were gaining only very superficial knowledge from traditional methods of instruction (Halloun & Hestenes 1985, Hestenes et al 1992). Rather than integrated conceptual understanding and creative problem solving, students were learning fragmented factual information and rote problem solving methods, while retaining many misconceptions about physics concepts. To gain some measure of student understanding, physicists developed the Force Concept Inventory (FCI) a simple multiple-choice test of basic concepts and common misconceptions about Newtonian physics of everyday events, written in simple language and requiring no sophisticated mathematics (Hestenes et al 1992). By administering the FCI at the beginning and the end of an introductory course, instructors could obtain a measure of gains in student conceptual learning. They could then experiment with different instructional approaches and test them for efficacy. These physicists showed that adopting a small number of non-traditional "promising practices" in course design and implementation could substantially increase student learning gains. These practices, and their basis in more general educational research on how people learn, are described in the following sections.

After a lag of several years, instructors in other STEM disciplines began to make similar observations about their students and to initiate similar efforts at improving instruction. The empirical approach of varying instructional methods and measuring effects on student learning has been called "scientific teaching" (Handelsman et al 2004; Wieman, 2007). Many of the DBE researchers doing this work are practicing scientists trained in their disciplines, who have learned educational research methods and taken up DBER as a sideline. Some schools of education have added DBER practitioners trained as educators to their faculties. In addition, some university science departments, particularly in physics but increasingly in other STEM disciplines, now include staff or tenure-track DBE researchers (NAS 2005) and are beginning to offer graduate training and degrees in DBER.

DBER is published in a variety of education journals, some general and some that are discipline specific, sponsored by STEM professional societies. A few scientific journals, including *Nature*, *Science, PLoS Biology,* and *Genetics* have also begun publishing DBER articles, generally in an education section. Table 1 lists some of the more widely read general and discipline-specific educational journals that publish DBER in life sciences.

DBER necessarily uses the language of education research, some of which may be unfamiliar to ARCDB readers. A list of educational terms used in this article and their definitions is provided following the Literature Cited.

How students learn

New ideas about teaching and learning began to receive public attention in the 1960s. Popular iconoclasts such as John Holt (1964, 1967) and Jonathan Kozol (1967), building on earlier ideas (Dewey 1916, Ausubel 1963), pointed out the shortcomings of passive learning for children of all ages, and advocated instead more student-centered, open classrooms that promoted active learning through hands-on experience, by doing rather than by simply listening, reading, and watching. These writers, at the time considered radicals, articulated ideas about optimal conditions for meaningful learning that have since been tested and validated by a large body of educational research. Also during the past three decades, advances in cognitive science have begun to elucidate the neural activities and synaptic changes that accompany learning. Results of research in both education and cognition were reviewed in the seminal National Research Council (NRC) report *How People Learn: Brain, Mind, Experience, and School* (Bransford et al 1999). The major conclusions from this research can be summarized as follows.

- Learning involves the elaboration of knowledge structures in long-term memory. According to this "constructivist" view of education (Dewey 1916, Ausubel 1963, Ausubel 2000), effective instruction must begin at the level of a student's prior knowledge (which may include misconceptions). New information unrelated to prior knowledge is difficult to learn and remember.
- No two learners are the same: learners differ in previous experience, previous instruction, preferred styles of learning, family background, cultural background, and so on. Diversity is an asset for collaborative work, because different members of a group bring different perspectives and skills to bear, but it can hamper learning for some students unless the level and mode of instruction are appropriate for all.
- Learning is promoted by frequent feedback, that is, ongoing testing of new knowledge as students are acquiring it. Educators call this "formative assessment," as opposed to "summative assessment," which refers to high-stakes exams given after an extended period of instruction. Formative assessment provides valuable feedback to both instructor and students. Do students understand the concept just presented or discussed? Can they transfer this understanding to apply the concept in a new situation?
- Effective learning requires awareness and questioning of one's own learning process: How well do I understand this? What information do I need to understand it better? What don't I understand yet? Do I understand it well enough to transfer it, that is, apply it to a new situation? Educators call this awareness "metacognition."

- Learning is enhanced in a community of learners who value the knowledge that is being learned. In early childhood this community is the family; at the university it could be a group of students working together to solve a problem or complete a research project.
- Learning changes the structure of the brain, and the extent of change increases with the degree of complexity, stimulation, and emotional involvement in the learning environment (Zull 2002). Active learning, in which a student's levels of motivation, curiosity, and attention are high, for example during a group effort to solve an intriguing problem, will be better retained than learning from relatively passive activities such as reading a text or listening to a lecture.
- Learning in a particular area of knowledge such as life sciences can be viewed as a continuum from novice to expert status, along which we would like to help our students progress. The knowledge of an expert constitutes a coherent structure into which new concepts can easily fit and from which relevant information can be efficiently retrieved. In contrast, new knowledge for the novice often appears to be a collection of unrelated facts, which are difficult to memorize and retain. In other words, experts see and make use of meaningful patterns and relationships in the information they possess, while novices cannot.

Application to the college classroom

These general conclusions apply to teaching and learning of STEM disciplines at the undergraduate level.

- Effective instruction must build on students' prior knowledge (which may include misconceptions that require correction).

- Instructors should be aware of the student diversity in their classrooms and use a variety of teaching modes to optimize learning for all students.
- Classes should include frequent formative assessment, to provide feedback to both instructors and students.
- Students should be encouraged to examine and monitor their own understanding of new concepts, for example, by explaining them to their peers.
- Students should be encouraged to work cooperatively and collaboratively in small groups.
- In order to bring about the neurological changes that constitute learning, students should spend time actively engaged with the subject matter, for example, discussing, diagramming, solving problems, working on a research project, etc., in addition to or in place of listening passively to a lecture, reading the textbook, or consulting web sites.

Most college STEM classes, particularly in large introductory courses, are not designed around these principles, and it can be argued that this is one reason for the high attrition rates and generally superficial learning among introductory students in STEM disciplines. Educators have shown that effective instruction requires not only disciplinary content knowledge, for example, expertise in life sciences, but also pedagogical content knowledge, that is, understanding of and ability to apply known educational principles. Because graduate and post-doctoral training in STEM disciplines seldom include any instruction in pedagogical practice, most university faculty are unaware of new knowledge about learning that could make their teaching more effective. Therefore, they simply teach the way they were taught in large classes, by traditional lecturing. We need to improve the way we teach undergraduates. The remainder of this article will discuss some of the evidence that applying the above principles to college classrooms can make a difference in how much and how well our students learn.

Evidence that research-based teaching at the college level increases student learning

Our best undergraduates, sometimes with little help from faculty, develop learning skills that incorporate the above principles, allowing them to progress toward expert knowledge regardless of how we teach them. However, many students, for whom studying means highlighting phrases in their lecture notes and textbooks and memorizing disconnected facts, fail to develop these skills and consequently learn very little. Is there good evidence that changes in teaching approaches at the college level can significantly enhance student learning?

Physicists were the first to obtain such evidence, following development of the FCI, which became nationally accepted during the 1990's as a way to gauge student learning of Newtonian mechanics. Administering the FCI as a pre-test at the start of a course and then again as a post-test at the end yielded a raw learning gain for each student. For comparison of students with different levels of incoming knowledge, each raw gain was divided by the maximum possible gain for that student, to arrive at a percentage normalized gain: <g>=100(post-test score – pre-test score)/(100 – pre-test score).

In attempts to increase the generally low normalized gains seen in traditional introductory courses, physics DBE researchers "transformed" their courses with new teaching approaches following the principles described above: more class time devoted to active learning, more group problem solving, frequent formative assessment, and so on. They carried out controlled studies, for example, the same instructor teaching the same syllabus through traditional lectures in one semester and then using the new approaches in the following semester (e.g. Beichner 2008).

Study after study indicated that students in the transformed courses substantially outperformed those in traditional courses. In a compelling landmark meta-analysis combining data from many such studies, R. R. Hake (1998) showed that for a sample of over 6,000 students in 55 introductory physics courses nation-wide, the average learning gains were nearly twice as high in transformed courses than in traditional courses.

Other STEM disciplines have lacked widely accepted assessment instruments comparable to the FCI until recently (see below). Nevertheless, several studies using some form of pre- and post-testing have also yielded results showing the greater efficacy of transformed courses. In the life sciences, an early study from the University of Oregon showed that students in the traditional introductory course learned substantially less than students in a "workshop" biology course, in which lecturing was almost entirely replaced by student group problem solving and other projects during class time (Udovic et al 2002). Knight and Wood (2005) showed in a controlled study that even an incremental change, substituting 30-40% of lecturing during class time with more engaging student-centered activities (described below), led to increases in normalized learning gains averaging about 30% in a large upper-division developmental biology course. Similar results have been reported in large introductory biology courses (e.g. Smith et al 2005, Armstrong et al 2007, Freeman et al 2007).

Clearly, concept inventories in life sciences would be valuable for continuation of this research (Garvin-Doxas et al 2007), and several have recently been published for various subdisciplines, including general biology (Klymkowsky et al 2003), genetics (Bowling et al 2008, Smith et al 2008b), and natural selection (Anderson et al 2002). Libarkin (2008) has compiled a comprehensive current listing and comparison of concept inventories in STEM disciplines.

Promising practices for increasing student learning

Many college faculty use Socratic dialog and student-centered group work in small classes and seminars, but believe there is no alternative to lecturing when confronted with hundreds of students in an auditorium with fixed seats. However, innovative instructors pursuing DBER have shown that there are indeed alternatives that can be more effective than lecturing for promoting student conceptual understanding. This research has identified several promising practices for transforming large classes (reviewed in Handelsman et al 2007, Froyd 2008). Table 2 summarizes nine of these practices compared with their counterparts in traditional instruction, and the subsequent paragraphs discuss their use and effects on student learning.

Froyd (2008) has introduced a useful rating of promising practices on two criteria: practicality of implementation (breadth of applicability to STEM courses, freedom from resource constraints, ease of transition for instructors), and evidence for efficacy in promoting increased student learning (from strongest evidence – multiple high-quality comparison studies, to weakest – descriptive application studies only). The paragraphs that follow include ratings of promising practices for these two criteria.

1. Content organization. The difference between preparing a course syllabus and formulating learning objectives is more profound than it may appear (Allen & Tanner 2007). The typical syllabus is instructor-centered; it lists the topics on which the instructor will lecture and assign out-of-class work, but it gives students little information about the level of understanding they should strive for or the skills they are to learn. In molecular biology, for example, the process of transcription can be understood at many levels, generally not distinguished in a syllabus. In contrast, learning objectives are student-centered and more explicit; they describe what a successful student should be able to do at the end of the course or unit. For example, students should be able to "name the principal enzyme that catalyzes transcription," or "explain the nucleotide sequence relationships between the two strands of the template DNA and the RNA product of transcription," or "diagram a step in the elongation of an RNA transcript, showing the local nucleotide sequences and strand polarities of both DNA strands and the RNA," or "predict the consequences for the transcription process if one of the four nucleoside triphosphates is unavailable."

The tasks above require different levels of understanding. A half century ago, the American educator Benjamin Bloom developed a convenient scheme for classifying these levels (Bloom & Krathwohl 1956), which became known as "Bloom's taxonomy of the cognitive domain" (Figure 1). Each of Bloom's six levels of understanding can be associated with verbs appropriate for a learning goal at that level: for example, ability to name an enzyme or describe a process requires only memorization of the relevant information (Level 1), whereas ability to predict an outcome (Level 3) or defend a principle based on evidence (Level 6) require deeper conceptual understanding. The verbs employed (Figure 1) describe an action or ability that can be assessed by asking students to carry it out. (Therefore, statements like "students should understand," or "appreciate," or "be aware of" are inappropriate learning objectives, since their achievement cannot be tested without more explicit performance-based criteria.) Because lower Bloom's levels are easiest to assess with multiple-choice and short-answer exams, many instructors in large STEM courses neither demand nor test for higher levels of understanding. Ongoing research on assessment in introductory biology courses indicates that the overwhelming majority of test items on final exams are Bloom's Level 1 (D. Ebert-May, personal communication). Most students learn at the level assessed on final exams; small wonder that they derive only superficial knowledge from such courses! To remedy this situation, instructors must aim for higher Bloom's levels in formulating course learning goals, and they must assess this understanding with appropriately challenging questions on their exams.

Course design around learning goals follows what Wiggins and McTighe (1998) termed the principle of backward design. The instructor first formulates the broad learning goals for students in the course, and then more specific learning objectives. Once these are decided on, she designs assessments (both formative and summative) to test for their achievement. Only then does she choose the most appropriate text or other reference materials and plan the learning activities in and outside of class that will most effectively lead to fulfillment of the objectives. Figure 2 compares traditional and backward design of STEM courses.

Froyd's (2008) implementation rating for the practice of course design around learning objectives is high (applicable to any STEM course, no significant resource constraints, no need for radical change in instructor's teaching methods). As for efficacy rating, there are no empirical studies (known to this author) that compare student learning in courses taught from syllabi and those built around learning objectives. However, it seems self-evident that more learning will occur in courses that explicitly set goals for high levels of conceptual understanding and require that students demonstrate achievement of these goals on exams and other course work.

2. Student organization. Organizing students into small groups for in-class and out-of-class work can transform the course experience from competitive to collaborative, allow students to learn from each other as well as from instructors, and help to involve students who might not otherwise become actively engaged with the course content (Tanner et al 2003). Groups can collaborate on regular homework assignments, longer term projects such as researching a topic and developing a poster presentation, and in-class work if the course includes problem solving and other active learning activities during class time.

The implementation rating for group organization is lower than for learning objectives, because it involves some additional instructor effort and decision making, regarding for example, how to form effective groups, facilitate their function, and help students develop collaborative skills (for specific references, see Froyd 2008). With regard to efficacy, much research in social science has shown that groups in general are more effective at complex problem solving than individuals (e.g. Brophy 2006), and that a group's effectiveness increases with the diversity of its members (Cox 1993, McLeod et al 1996, Guimera et al 2005). Comparative studies and meta-analyses have provided strong evidence that group work in STEM courses contributes to increased student learning (e.g. Johnson et al 1998, Springer et al 1999). There is additional evidence in connection with in-class active learning in groups, discussed in the context of Practice #4 below.

There are also other arguments for encouraging group work. With the increasing popularity of distance learning, the opportunity for student collaborative intellectual endeavor is one of the major advantages that resident universities can provide, and universities should exploit it. As Astin (1993) concluded in his book of the same name, "What Matters in College" are the relationships students build with each other and with their instructors. Moreover, development of group-work skills is important in preparing students for the "real world." When students comfortable with the traditional, individual, competitive learning mode object to group work, the instructor can point out that when they join the workplace they will probably be part of a team, whose members they did not choose, and that they need to learn how to contribute effectively to group work as an important part of their education.

3. Feedback. One of the key aspects of effective instruction identified by the 1999 NRC study was feedback to students during the learning process (Bransford et al 1999). Traditional courses provide feedback by returning graded homework and exams to students, usually too late to be of optimal use because the class has moved on to other topics. In contrast, in-class formative assessment provides immediate feedback to both students and instructors on how well a concept under discussion is being understood. The results can be eye-opening, particularly for instructors considered engaging and effective lecturers, when they find that only a fraction of their students have understood a seemingly lucid explanation. Students may be surprised as well, since the concept as presented may have seemed clear until they were asked to explain or apply it. But most important, awareness of a problem in understanding allows the class to address it immediately and in context, when it is most meaningful to students.

In the 1990's, the physicist Eric Mazur began to obtain this kind of feedback by posing multiple-choice questions ("ConcepTests") to his class that required application of the concept under discussion (Mazur 1997, Crouch & Mazur 2001). Initially, students indicated their choices by a show of hands or by holding up different colored cards. More recently the audience response devices known as "clickers," developed originally for TV game shows, have made this kind of formative assessment more convenient and powerful (Wood 2004, Barber & Njus 2007). Each student has a clicker, generally with five buttons labeled A-E, and a receiver is connected to the instructor's computer. When students respond to a multiple-choice question, their answers are recorded electronically, and a histogram of the results is displayed to the instructor and the class. How the instructor can respond to this information is discussed in the following section under active learning, but the benefits for formative assessment are clear: student responses are independent and anonymous; they are recorded for later analysis by the instructor if desired; a problem with understanding is immediately apparent, and the class can address it on the spot.

Frequent quizzes can also serve as formative assessment, and research has shown that taking tests after studying leads to significantly more learning than studying alone (Karpicke & Roediger 2008, Klionsky 2008). Moreover, the results of quizzes (and in-class concept questions) are valuable to the instructor in designing appropriate exam questions (summative assessments). Other kinds of formative assessment include the "one-minute-paper" (Angelo & Cross 1993, Stead 2005), where students are asked to write down and hand in anonymously a brief statement of what they found most difficult and what they found most interesting during the preceding class. This encourages immediate reflection on the part of students and informs the instructor of possible problems. Students can also be asked to comment, positively or negatively, about general aspects of the course. Other forms of formative assessment are considered in the following section on in-class active-engagement activities. Any activity that requires students to apply concepts just discussed can provide useful feedback about conceptual understanding to both students and instructors.

Ease of implementing formative assessment is high; instructors do not need to change the way they teach to obtain occasional feedback during class, although the results of such feedback may well change their teaching approaches as discussed further below. Clickers are an added expense for students, who generally purchase a clicker at the bookstore and can re-sell it if they wish at the end of the course (Barber & Njus 2007). With regard to evidence for efficacy, formative assessment is generally coupled with in-class activities and so cannot be easily evaluated in isolation. Studies demonstrating the value of both these practices in combination are discussed in the following section.

4. In-class learning activities. In large STEM classes, the traditional learning activity is the lecture. Even students who are paying close attention to the lecturer are engaged primarily in the passive recording of information, with little time for reflection. There is compelling evidence from all STEM disciplines that replacing some or all lecturing with in-class activities that actively engage students can substantially increase student learning gains. Of the promising practices reviewed here, this one, especially when combined with #2, students working in groups, and #3, frequent formative assessment, has produced the most impressive improvements in study after study. Many possible in-class activities – brainstorming, reflection followed by discussion with a neighbor and reporting to the class ("think-pair-share"), concept mapping, group problem solving, and more – are well described in the excellent book *Scientific Teaching* (Handelsman et al 2007) and in the series of features titled "Approaches to Biology Teaching and Learning" by D. Allen and K. Tanner in the online journal *CBE-Life Sciences Education* (Allen & Tanner 2002, Allen & Tanner 2003b, Allen & Tanner 2003a, Allen & Tanner 2005). Table 3, adapted from the Handelsman et al. book, compares the traditional lecture presentation of a few topics with corresponding active learning alternatives.

In-class concept questions, particularly when used with clickers, can be a powerful active learning tool. When a challenging multiple-choice concept question is presented to the class and the initial response is about evenly split between the correct choice and one of the incorrect ones (distracters), a "teachable moment" occurs: students may be amused or surprised, but they want to know who is right and who is wrong, and they have become emotionally involved (Wood

2004). Rather than revealing the correct answer, or trying to explain the concept again, the instructor interested in promoting active learning asks the students to discuss their answers in small groups, trying to convince their neighbors that one or the other of the two choices is correct. Following a few minutes of discussion, the instructor calls for another vote, and almost invariably, the majority of students will now choose the correct answer, which is then revealed and discussed. Students are often better able than the instructor to identify flawed reasoning among their peers and convince them of the correct reasoning. Mazur named this phenomenon "peer instruction" in his delightful book of the same name (Mazur 1997, Crouch & Mazur 2001). It could be argued that less knowledgeable students are simply influenced during discussion by peer pressure from neighbors they perceive to be more knowledgeable, but a recent study indicates that, on the contrary, students are learning during the discussion (Smith et al 2008a).

Clicker questions, to be effective, must be conceptual and challenging. Ideally they should include distracters based on known student misconceptions. Writing good ones is difficult but essential; questions that simply test factual recall of recently presented information do not engage students and are of little pedagogical use. Clicker questions are also not useful if the instructor, after the initial vote, simply indicates the correct answer and then moves on; student discussion before revealing the correct answer as well as after is key to learning. For additional guidance on writing good clicker questions and their effective use, see Beatty et al. (2006) and Wieman et al. (2007).

Concept questions generally pose well-defined, discrete problems, directly related to the immediate class content. Other valuable problem-based activities can be based on larger, more open-ended questions that groups of students may work on for a larger fraction of the class period and continue outside of class (see following section). But all are examples of building instruction around student engagement with a problem, rather than around a body of factual information. Prince and Felder (2007) have contrasted "deductive teaching" – transmitting facts, abstract concepts, and finally (maybe) discussing their application to real-world problems, with "inductive teaching" – starting by posing a real-world problem to students, and letting them uncover the relevant concepts and facts in the process of solving it. When teaching is deductive, student motivation to learn facts and concepts is often primarily extrinsic, driven by desire to obtain a good grade, and the instructor must try to keep students engaged with assertions that this knowledge will be important in their future studies or careers. By contrast, when teaching is inductive, the students are presented with a real world scenario that they are likely to find interesting, and their motivation is intrinsic, based on desire to find a solution. Inductive approaches have been given a variety of labels, including inquiry-based, problem-based, project-based, case-based, question-driven, and discovery learning (reviewed in Prince & Felder 2007). Their scope can range from a series of related clicker questions in a single class period (Beatty et al 2006) to a complex problem requiring several weeks of work, in which new information is provided in response to requests from students for data or results of specific experimental tests. Problem-based and case-based learning in which students are presented with a set of disease symptoms asked to arrive at a diagnosis are used extensively in medical education (beyond the scope of this review; see Albanese & Mitchell 1993).

Implementing in-class active learning is more difficult than the other promising practices so far discussed. While design of a new course around the active learning model may require no more effort than preparing the lectures for a new traditional course, transformation of a traditional course requires the additional work of creating effective in-class activities and formative assessments. In addition, auditorium-style classrooms with fixed seating are poorly suited for interactive group work. A few institutions have installed large classrooms with café-style seating, which greatly facilitates student-centered teaching (see Beichner 2008), and more should be built to encourage course transformation. More important and perhaps most difficult for some instructors, teaching effectively in the new mode requires a willingness to let go of some control in the classroom, as well as a change in perspective, from instructor-centered teaching to student-centered learning. Instructors must give up the widely held "transmissionist" view that students must be told everything they need to know, and instead adopt the realization that not only are students in an encouraging environment capable of learning a great deal on their own, but that they must develop the ability to do so in order to become either successful scientists or well-informed citizens.

Balanced against the difficulty of changing one's teaching approach to a more student-centered mode is the clear evidence from DBER that doing so can substantially increase student learning gains. And complete restructuring is not necessary; even incremental changes can have a significant effect (Knight & Wood 2005). Other evidence from the life sciences has been mentioned (Udovic et al 2002, e.g. Armstrong et al 2007, Freeman et al 2007), and additional references can be found in Froyd (2008).

5. Out-of-class learning activities. A frequent concern of instructors contemplating introduction of clickers and other active-learning activities into their classrooms is that they will no longer be able to "cover" all the necessary content. First of all, this may not be a bad thing. More "coverage" does not necessarily mean more learning, and it can be argued that deep student understanding of a few important concepts is more valuable than superficial exposure to many. Nevertheless, the content issue is real, because it can affect student preparation for subsequent courses and standardized tests such as the MCAT. A solution to this dilemma lies in placing more of the responsibility on the students themselves for learning basic concepts, and again, recent technology makes this solution more practical. Using an approach that physicists have called "Just-in-Time Teaching" (JiTT; Novak et al 1999), students are assigned reading and homework to be submitted online to a course web site before a topic is considered in class. The instructor can then scan the results (sampling randomly if the class is large), determine which concepts students seem to have grasped on their own, and then focus activities in the upcoming class on concepts they found difficult. Students at first may resist taking this responsibility, but learning to do so is again preparation for later advanced study and the real world, where one cannot expect to receive a lecture whenever a new concept must be learned. An extension of JiTT, which may be more palatable to students, is the "inverted classroom" approach (Lage et al 2000). Students are provided in advance of class with access to podcasts of a PowerPoint lecture by the instructor, or some other multimedia presentation that serves the information transmission function of the traditional in-class lecture. Class time can then be devoted to solving problems, doing experiments, or other active learning activities, without concerns about inadequate coverage of content.

Implementation of these approaches is quite simple using the Internet and one of the Web-based course management programs that are now available at most universities to instructors of large classes. Many faculty have reported not only increased student learning with these methods, but also strong endorsement by students once they realized how much they were learning (e.g. Klionsky 2004, Silverthorn 2006).

6. Student-faculty interaction in class. Many students, who have become comfortable with traditional courses, may object to the new teaching approaches and the demands that are placed on them in transformed courses: more responsibility for learning outside of class, the need to attend class regularly, the emphasis on group work, refusal of the instructor to tell them all the things they need to know, and so on. The best way to confront these objections, in the author's experience as well as in the literature (e.g. Silverthorn 2006), is to encourage buy-in by being open with students about the pedagogical reasons for new approaches and the benefits they bring. For example, the instructor can spend a few minutes introducing them to the concept of Bloom's levels, and remind them that the skills likely to determine their success in graduate work and the job market correspond to Levels 3-6, not Levels 1 and 2 (Figure 1). Show them evidence from DBER that group work and active learning can substantially increase learning gains, and point out, as mentioned above, that these activities will better prepare them for life in the real world. But also be sympathetic and supportive of students struggling with these changes. Students also must also shift their perceptions about teaching and learning in order to succeed with the new instructional approaches (Silverthorn 2006).

The active learning activities discussed above greatly increase the amount of student-faculty interaction in comparison with traditional lecture settings. Use of clickers with peer instruction, in particular, is an easy way to move classes from one-way transmission of information to interactive dialogs between instructor and students, and between students, with instructional benefits already described.

7. Student-faculty contact outside of class. Umbach and Wawrzinski (2005) cite several studies showing that in general, student learning is enhanced by increased student-faculty contact, suggesting that faculty, as time permits, should provide more opportunities for interaction than simply holding office hours for those (often few) students who will make use of them. Additional interactions can include brief get-acquainted visits by invitation to the instructor's office, or for larger courses, virtual communication through emails to the class, moderated discussion forums, or use of social networking environments like Facebook.com.

8. Use of teaching assistants. Many instructors of large STEM courses have help from one or more teaching assistants (TAs), whose principal tasks are grading of homework and exams and perhaps conducting recitation sessions where they go over lecture material and homework problem solutions. If TAs are made part of the course transformation process and given minimal pedagogical training (e.g. reading of Handelsman et al 2007), they can serve as valuable facilitators in class for discussion of clicker questions or group work on problems. In addition, they will have gained a new kind of teaching experience that can serve them well in the future if they should go on to become faculty members themselves. Many institutions, for example those involved in the CIRTL Network (CIRTL), provide such training to STEM graduate students in Preparing Future Faculty programs.

9. Student laboratories. As one solution to the problem of inadequate STEM education for undergraduates, the Carnegie Foundation's Boyer Commission Report (1998) recommended that research universities integrate their research and teaching missions by involving more students in the process of research. In the traditional "cookbook" labs associated with many large introductory lecture courses, students perform prescribed exercises in which they may learn some laboratory techniques but generally gain little understanding of scientific inquiry. At the other end of the lab experience spectrum (see Figure 3), some undergraduates become apprentices in faculty laboratories, working alongside graduate students and postdocs on faculty research projects that often result in publication and learning how science is done by doing it. Although this experience is highly desirable, most departments can provide it to only a fraction of their majors. Between these extremes, some departments have developed a variety of inquiry-based laboratory courses designed to introduce large numbers of students to the process of research (reviewed in Weaver et al 2008). These courses range from guided inquiry labs to open-ended group research projects that may result in publications by undergraduates (e.g. Hanauer et al 2006). Faculty who supervise these courses often design them to yield results that contribute directly to their own research programs.

Implementation of inquiry-based courses in place of traditional labs may require additional resources, including more extensive training of TAs. Although Froyd (2008) rates this promising practice low in terms of evidence for efficacy, several studies, in addition to the two cited immediately above have shown that engagement of students with real research problems is one of the most effective ways to move students along the path from novice to expert (Nagda et al 1998, Lopatto 2004, Luckie et al 2004, Seymour et al 2004). Reported benefits to students in inquiry-based curricula include deeper understanding of content, increased confidence in their ability to understand and do science, more positive attitudes about science, and lower attrition rates, in comparisons with students who experience only traditional lab courses. These gains are particularly evident among underrepresented minority students (Nagda et al 1998, Russell et al 2007). Thus the benefits of this promising practice can include not only increased student learning and higher retention of students in the major (especially if inquiry-based labs are introduced early in the curriculum), but also contributions to faculty research.

Conclusion: the dual functions of biology education

There are two important purposes for the introductory biology courses we teach. One is to attract, motivate, and begin preparing the next generation of biologists, including the research stars of the future. The other is to help the large majority of our students, who will not become biologists or even scientists, to achieve minimum biological literacy and to understand the nature of science, the importance of empirical evidence, and the basic principles that underlie biological systems. They will need this knowledge as 21st century citizens of this country and the world to make intelligent decisions about voting, health care, conflicting claims in the news media, energy policy, climate change, conservation issues, and so on.

Traditional teaching methods do not prevent the progress of superior students from introductory to upper-level courses to graduate training, where they may become experts in their fields and develop into skilled researchers. But the traditional methods fail the majority of students, who leave our introductory courses viewing biology as a large collection of disconnected facts, which have little relevance to their daily lives and will soon be forgotten. Part of the problem, as described in this review, lies not in what we teach them but how we teach it. We must do better! Widespread adoption of the research-based promising practices described here will help.

LITERATURE CITED

Albanese M, Mitchell S. 1993. Problem-based learning: A review of the literature on its outcomes and implementation issues. *Academic Medicine* 68:52-81

Allen D, Tanner K. 2002. Approaches to cell biology teaching: questions about questions. *Cell Biol. Educ.* 1:63-7

Allen D, Tanner K. 2003a. Approaches to cell biology teaching: learning content in context--problem-based learning. *Cell Biol. Educ.* 2:73-81

Allen D, Tanner K. 2003b. Approaches to cell biology teaching: mapping the journey-concept maps as signposts of developing knowledge structures. *Cell Biol. Educ.* 2:133-6

Allen D, Tanner K. 2005. Infusing active learning into the large-enrollment biology class: seven strategies, from the simple to complex. *Cell Biol. Educ.* 4:262-8

Allen D, Tanner K. 2007. Putting the horse back in front of the cart: using visions and decisions about high-quality learning experiences to drive course design. *CBE Life Sci. Educ.* 6:85-9

- **The above articles by Allen and Tanner, plus another by Tanner, Chandler, and Allen below, provide excellent practical introductions to several of the promising practices discussed in the text.**

Anderson DL, Fisher KM, Norman GJ. 2002. Development and evaluation of the Conceptual Inventory of Natural Selection. *J. Res. Sci. Teach.* 39:952-78

Angelo TA, Cross PK. 1993. *Classroom Assessment Techniques: A Handbook for College Teachers*. San Francisco: Jossey-Bass

Armstrong N, Chang SM, Brickman M. 2007. Cooperative learning in industrial-sized biology classes. *CBE Life Sci. Educ.* 6:163-71

Astin AW. 1993. *What Matters in College: Four Critical Years Revisited*. San Francisco: Jossey-Bass

Ausubel D. 1963. *The Psychology of Meaningful Verbal Learning*. New York: Grune and Stratton

Ausubel D. 2000. *The Acquisition and Retention of Knowledge: A cognitive view*. Boston: Kluwer Academic Publishers

Barber M, Njus D. 2007. Clicker evolution: seeking intelligent design. *CBE Life Sci. Educ.* 6:1-8

Beatty ID, Leonard WJ, Gerace WJ, Dufresne RJ. 2006. Question driven instruction: Teaching science (well) with an audience response system. In *Audience Response Systems in Higher Educatin: Applications and Cases*, ed. DA Banks. Hershey, PA: Information Science Publishing

Beichner R. 2008. The SCALE-UP Project: A student-centered active learning environment for undergraduate programs. Presented at BOSE Conference on Promising Practices - Innovation in Undergraduate STEM Education, Washington, DC http://www7.nationalacademies.org/bose/PP_Commissioned_Papers.html

Bloom BS, Krathwohl DR. 1956. *Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook 1: Cognitive Domain*. New York: Longmans

Bowling BV, Acra EE, Wang L, Myers MF, Dean GE, et al. 2008. Development and evaluation of a genetics literacy assessment instrument for undergraduates. *Genetics* 178:15-22

Boyer EL. 1998. Report of the Boyer Commission on Educating Undergraduates in the Research University. *Reinventing undergraduate education: A blueprint for America's research universities*, The Carnegie Foundation, Stony Brook, NY

Bransford JD, Brown AL, Cocking RR, eds. 1999. *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Research Council (National Academies Press)

- **The classic review of educational and cognitive science research on how learning occurs and the conditions that foster it.**

Brophy DR. 2006. A comparison of individual and group efforts to creatively solve contrasting types of problems. *Creativity Res*. J. 18:293-315

Caldwell JE. 2007. Clickers in the large classroom: current research and best-practice tips. *CBE Life Sci Educ* 6:9-20

CIRTL. Center for the Integration of Research, Teaching, and Learning. Univ. of Wisconsin, Madison
http://www.cirtl.net/

Cox J. 1993. *Cultural Diversity in Organizations: Theory, Research, and Practice*. San Francisco: Berrett-Koehler Publishers

Crouch CH, Mazur E. 2001. Peer instruction: Ten years of experience and results. *Am. J. Phys.* 69:970-7

DeHaan RL. 2005. The impending revolution in undergraduate science education. *J. Sci. Educ. Technol*. 14:253-9

Dewey J. 1916. *Democracy and Education.* New York: Macmillan

Freeman S, O'Connor E, Parks JW, Cunningham M, Hurley D, et al. 2007. Prescribed active learning increases performance in introductory biology. *CBE Life Sci. Educ.* 6:132-9

Froyd J. 2008. White paper on promising practices in undergraduate STEM education. Presented at BOSE Conference on Promising Practices - Innovations in Undergraduate STEM Education, Washington, DC http://www7.nationalacademies.org/bose/PP_Commissioned_Papers.html

- **A good summary of the evidence with additional references for most of the promising practices described in this review.**

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. *CBE Life Sci. Educ.* 6:277-82

Glenn J. 2000. *Before It's Too Late* (The Glenn Report), Dept. of Education, Washington DC http://www.ed.gov/americacounts/glenn

Guimera R, Uzzi B, Spiro J, Amaral LA. 2005. Team assembly mechanisms determine collaboration network structure and team performance. *Science* 308:697-702

Hake RR. 1998. Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *Am. J. Phys.* 66: 64-74

Halloun IA, Hestenes D. 1985. Common-sense concepts about motion. *Am. J. Phys.* 53: 1056-65

Hanauer DI, Jacobs-Sera D, Pedulla ML, Cresawn SG, Hendrix RW, Hatfull GF. 2006. Inquiry learning. Teaching scientific inquiry. *Science* 314:1880-1

Handelsman J, Ebert-May D, Beichner R, Bruns P, Chang A, et al. 2004. Scientific teaching. *Science* 304:521-2

Handelsman J, Miller S, Pfund C. 2007. *Scientific Teaching*. New York, NY: W. H. Freeman

- **An excellent, brief practical guide to most of the promising practices described in this review. Highly recommended for all STEM instructors.**

Hestenes D, Wells M, Swackhamer G. 1992. Force concept inventory. *Physics Teacher* 30:141-58

Holt J. 1964. *How Children Fail.* New York: Pitman

Holt J. 1967. *How Children Learn.* New York: Pitman

Johnson DW, Johnson RT, Smith KA. 1998. Cooperative learning returns to college: what evidence is there that it works? *Change* 30:26-35

Karpicke JD, Roediger HL, III. 2008. The critical importance of retrieval for learning. *Science* 319:966-8

Klionsky D. 2004. Talking biology: teaching outside the textbook, and the lecture. *Cell Biol. Educ.* 3:204-11

Klionsky D. 2008. The quiz factor. *CBE Life Sci. Educ.* 7:265-6

Klymkowsky MW, Garvin-Doxas K, Zeilik M. 2003. Bioliteracy and teaching efficacy: what biologists can learn from physicists. *Cell Biol. Educ.* 2:155-61

Knight JK, Wood WB. 2005. Teaching more by lecturing less. *Cell Biol. Educ*. 4:298-310

Kozol J. 1967. Death at an Early Age. Boston: Houghton-Mifflin

Lage MJ, Platt GJ, Treglia M. 2000. Inverting the classroom: A gateway to creating an inclusive learning environment. *J. Econ. Educ.* 31:30-43 http://www.sba.muohio.edu/plattgj/eco201

Libarkin J. 2008. Concept inventories in higher education science. Presented at Promising Practices - Innovations in Undergraduate Stem Education, Washington, DC http://www7.nationalacademies.org/bose/PP_Commissioned_Papers.html

Lopatto D. 2004. Survey of undergraduate research experiences (SURE): first findings. *Cell Biol. Educ.* 3:270-7

Luckie DB, Maleszewski JJ, Loznak SD, Krha M. 2004. Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of "Teams and Streams". *Adv. Physiol. Educ.* 28:199-209

Mazur E. 1997. *Peer Instruction: A User's Manual.* Saddle River: Prentice Hall

McLeod PO, Lobel SA, Cox TH. 1996. Ethnic diversity and creativity in small groups. *Small Group Research* 27:248-65

Nagda BA, Gregerman SR, Jonides J, von Hippel W, Lerner JS. 1998. Undergraduate student-faculty research partnerships affect student retention *Rev. Higher Educ.* 22:55-72

NAS. 2004. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press, Washington DC http://books.nap.edu/catalog/11463.html

NAS. 2005. National Academies Workshop on Education Research Positions in STEM Disciplinary Departments http://www7.nationalacademies.org/cfe/STEM_Disciplines_Agenda.html

Novak G, Gavrin A, Christian W, Patterson E. 1999. *Just-in-Time Teaching: Blending active learning with Web technology*. San Francisco: Pearson Benjamin Cummings http://webphysics.iupu.edu/jitt/jitt.html

Prince M, Felder R. 2007. The many faces of inductive teaching and learning. *J. Coll. Sci. Teach.* 36:14-20

- **A good review of instructional approaches that begin with presentation of real-world problems to students and challenge them to discover the facts and concepts they need for a solution.**

Russell SH, Hancock MP, McCullough J. 2007. The pipeline. Benefits of undergraduate research experiences. *Science* 316:548-9

Seymour E, Hewitt S. 1997. *Talking About Leaving: Why Undergraduates Leave the Sciences.* Boulder, CO: Westview Pres

Seymour E, Hunter AB, Laursen SL, Diatonic T. 2004. Establishing the benefits of research experiences for undergraduates in the sciences: first findings from a three-year study. *Science Educ.* 88:493-534

Silverthorn DU. 2006. Teaching and learning in the interactive classroom. *Adv. Physiol. Educ*. 30:135-40

Smith AC, Stewart R, Shields P, Hayes-Klosteridis J, Robinson P, Yuan R. 2005. Introductory biology courses: a framework to support active learning in large enrollment introductory science courses. *Cell Biol. Educ.* 4:143-56

Smith MK, Wood WB, Adams WK, Wieman C, Knight JK, et al. 2008a. Why peer discussion improves student performance on in-class concept questions. *Science* in press

Smith MK, Wood WB, Knight JK. 2008b. The Genetics Concept Assessment, a new concept inventory for gauging student understanding of genetics. *CBE Life Sci. Educ.* 7:422-430

Springer L, Stanne ME, Donovan SS. 1999. Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: A meta-analysis. *Rev. Educ. Res.* 69:21-51

Stead DR. 2005. A review of the one-minute paper. *Active Learning in Higher Educ.* 6:118-31

Stryer L, ed. 2003. *Bio2010: Transforming Undergraduate Education for Future Research Biologists.* Washington, DC: National Research Council (National Academies Press

Tanner K, Chatman LS, Allen D. 2003. Approaches to cell biology teaching: cooperative learning in the science classroom--beyond students working in groups. *Cell Biol. Educ.* 2:1-5

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* 52:272-81

Umbach PD, Wawrzynski MR. 2005. Faculty do matter: The role of college faculty in student learning and engagement. *Res. in Higher Educ.* 46:153-84

Weaver GC, Russell DB, Wink DJ. 2008. Inquiry-based and research-based laboratory pedagogies in undergraduate science. *Nature Chem. Biol.* 4:577-80

- **A good review of inquiry-based curricular innovations and their utility for introducing more students to the process of research.**

Wieman, C, 2007. Why not try a scientific approach to science education? *Change* 39:9-15

Wieman C, Perkins K, Gilbert S, Benay F, Kennedy S, et al. 2008. *Clicker Resource Guide: An instructors guide to the effective use of personal response systems (clickers) in teaching.* Vancouver BC, Canada: Univ. of British Columbia http://www.cwsei.ubc.ca/resources/files/Clicker_guide_CWSEI_CU-SEI_04-08.pdf

- **A useful introductory guide to clickers and their effective use to promote active learning through in-class concept questions.**

Wiggins G, McTighe J. 1998. *Understanding by Design.* Alexandria, VA: Association for Supervision and Curriculum Development

Wood WB. 2004. Clickers: A teaching gimmick that works (Resource Review). *Devel. Cell* 7:796-8

Zull JE. 2002. *The Art of Changing the Brain.* Sterling, VA: Stylus Publ. Co.

A book for educators on the neurobiology of learning.

ARTICLE COMPONENTS

KEY WORDS: Active learning, concept inventories, course transformation, discipline-based educational research (DBER), formative assessment, pedagogy.

ABSTRACT:

A growing revolution is underway in the teaching of introductory science to undergraduates. It is driven by concerns about American competitiveness as well as results from recent educational research, which explains why traditional teaching approaches in large classes fail to reach many students and provides a basis for designing improved methods of instruction. Discipline-based educational research in the life sciences and other areas has identified several innovative promising practices and demonstrated their effectiveness for increasing student learning. Their widespread adoption could have a major impact on the introductory training of biology students.

TERMS/DEFINITIONS

Assessment: Testing

Formative assessment: Frequent, ongoing testing, usually during class, with the goal of monitoring understanding and providing feedback rather than judging performance. Converse: summative assessment.

Summative assessment: High-stakes testing at the end of an instructional unit or course to judge student performance, e.g. mid-term and final exams.

Constructivist: The view that individual learners must build their own knowledge structures, from experience and instruction, on a foundation of prior knowledge. Converse: transmissionist.

Transmissionist: As used here, the view that learning can or must occur by transmission of knowledge to the learner from an instructor.

Metacognition: The process of monitoring one's own learning process and level of understanding.

Distracters: The incorrect choices in a multiple-choice question.

Transfer: Application of knowledge learned in one context to a problem in a different context; e.g. use of information learned in a chemistry course about the properties of water to explain why lipid bilayer membranes are stable in cells.

Instructor-centered: Designed around the knowledge the instructor wishes to transmit to students; focused on the instructor's teaching process.

Student-centered: Designed around the needs, abilities, prior knowledge and diversity of students; focused on the student's learning process.

ACRONYMS:

DBER:	Discipline-based educational research
FCI:	Force concept inventory
LSER:	Life sciences education research
MCAT:	Medical college admission test
STEM:	Science, technology, engineering, and mathematics
TA:	Teaching assistant

MAJOR POINTS OF THE ARTICLE:

1. We must improve the undergraduate teaching of biology and other STEM disciplines if we are to remain competitive in the global economy and educate American citizens adequately.
2. Recent research in educational psychology, cognitive science, and neurobiology has yielded important new insights into how people learn and the conditions that are optimal for learning.
3. Discipline-based educational research (DBER) has led to development of teaching approaches based on these insights (promising practices), and has provided extensive evidence that these approaches can be substantially more effective than traditional lecturing.
4. These promising practices vary in their ease of implementation, but even their partial adoption can lead to significant gains in student learning

5. We should be applying these promising practices widely to the instruction of STEM undergraduates; doing so could have a major impact on the education of biology students.

ANNOTATED REFERENCES: See bold-faced, bulleted entries in Literature Cited.

FIGURE LEGENDS

Figure 1. Bloom's levels of understanding.

Originally termed Bloom's taxonomy of the cognitive domain, this schema defines six levels of conceptual understanding, according to the processes that students at each level are capable of (Bloom & Krathwohl 1956). The italicized verbs have been added to the original hierarchy; they indicate performance tasks that test achievement of learning goals at each level. Fine distinctions in the hierarchy are difficult, and some educators prefer to classify goals on only three levels: low (1,2), medium (3,4) and high (5,6). (Based on Allen & Tanner 2002.)

Figure 2. Schematic comparison of standard and backward course design

Figure 3. The range of student laboratory experiences, from verification exercises ("cookbook labs") to apprenticeship in a faculty research laboratory. Levels of student responsibility and autonomy increase from left to right. (Adapted from Weaver et al 2008.)

TABLES

Table 1. A partial listing of journals that publish Life Sciences Education Research ‡

General Scientific Journals

Genetics
Nature journals
Science
PLoS Biology *

Education journals sponsored by professional societies

*Advances in Physiology Education, 2001- (*Amer. Physiol. Soc.) *†
Biochemistry and Molecular Biology Education, 2006- (Amer. Soc. Biochem. and Mol. Biol.) †
CBE-Life Sciences Education, 2002- (Amer. Soc. Cell Biol.) *†
Journal of Biological Education, 1990- (British Institute of Biology) *
Microbiology Education Journal (Amer. Soc. Microbiol.) †
Frontiers in Ecology and the Environment (Ecol. Soc. of Amer.)

General education journals

American Biology Teacher (Natl. Assoc. Biol. Teach.) * †
Bioscene: Journal of College Biology Teaching *
BioScience (Amer. Inst. of Biol. Sci.)
International Journal of the Scholarship of Teaching and Learning * †
Journal of College Science Teaching (Natl. Sci. Teach. Assoc.)

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‡ For additional journal listings, see Dolan (2007).

* Open access.

† Higher standards: research articles require assessment and outcomes evidence for efficacy of a new course or intervention, rather than simply descriptions of practice.

Table 2. Comparison of traditional practices with corresponding research-based promising practices for nine aspects of large course design and implementation in STEM disciplines

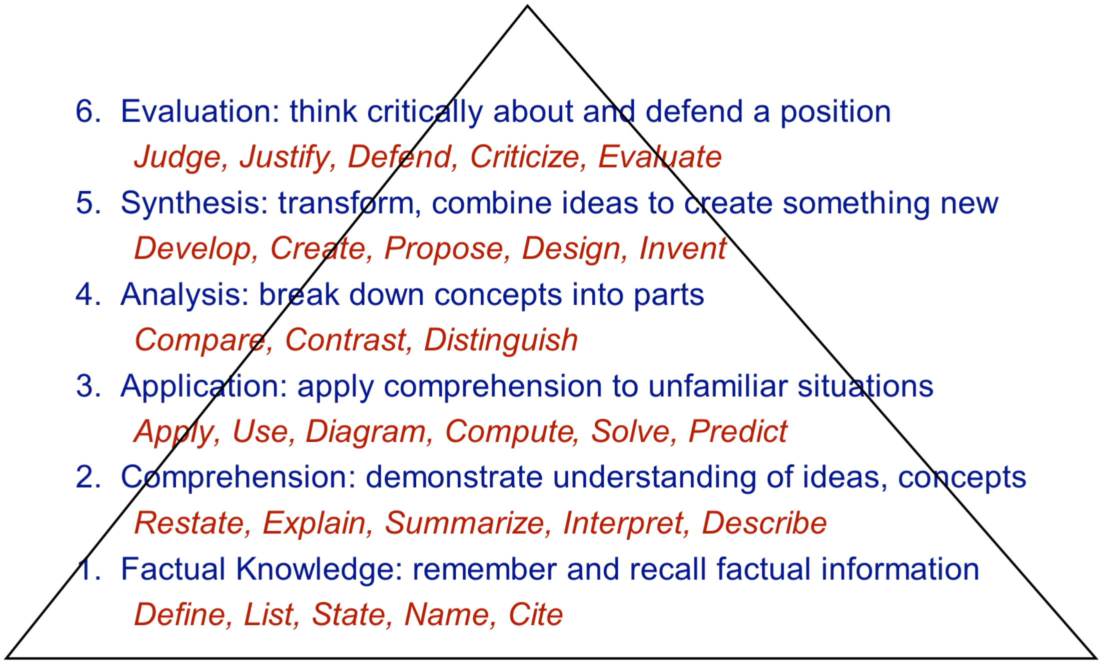
Course aspect	Traditional Practice	Research-based Promising Practice
1. Content organization	Prepare a syllabus, describing the topics that the instructor will present in class.	Formulate specific student learning objectives, in the form of "after this course, students will be able to . . . "
2. Student organization	Most student work is done individually and competitively	Most student work is done cooperatively, in small groups.
3. Feedback	Grading based primarily or entirely on summative assessments, i.e., midterm and final exams.	Feedback to instructor and students provided continually through in-class formative assessments
4. In-class learning activities	Instructor transmits information by lecturing. Some questions may be posed to students, but only a small subset of the class is likely to participate in discussion.	All students spend most or all class time engaged in various active-learning activities (see text), facilitated by instructor and TAs. Many of these activities also serve to provide formative assessment.
5. Out-of-class learning activities	Students read the text and may do assigned homework to practice application of concepts previously presented in class	Students read and do assigned homework on material not yet dealt with in class and post results online for instructor to review before class.
6. Student	Students are expected to accept	Instructor explains the pedagogical

faculty interaction in class	the teaching mode chosen by the instructor, and to infer how they should study and what they should learn from the instructor’s lectures and assignments.	reasons for the structure of course activities to encourage student buy-in, and explicitly and frequently communicates the course learning goals to students.
7. Student-faculty interaction out of class	Students must initiate out-of-class interaction with each other and with the instructor, e.g., by coming to office hours.	Instructor facilitates interaction with and among students, by setting up online chat rooms, encouraging group work on homework assignments, and communicating with students electronically.
8. Use of teaching assistants	TAs are used mostly for grading assignments and exams, and may conduct recitation sessions in which they demonstrate problem solving methods or further explain lecture material.	TAs receive some initial instruction in basic pedagogy and serve as facilitators for in-class group work and tutorial sessions in which small student groups work out problems on their own.
9. Student laboratories	Students carry out exercises that demonstrate widely used techniques or verify important principles, by following a prescribed protocol. (“Cookbook” labs)	Students are required to solve a research problem, either defined (e.g. identify an unknown) or more open-ended (e.g. determine whether commonly used cosmetic products are mutagenic) and learn necessary experimental techniques and concepts in the process. (Inquiry-based labs)

Table 3. Comparisons between presentation of topics in traditional lecture format and corresponding active learning activities

Concept	Passive lecture	Active class
Differential gene expression	Every cell in an organism has the same DNA, but different genes are expressed at different times and in different tissues. This is called differential gene expression.	If every cell in an animal has the same DNA, then how can cells of different tissues be so different? Discuss this question with your neighbor and generate a hypothesis.
DNA structure and replication	Complementary base pairing is the basis for the mechanism of DNA replication.	What do you know about the structure of DNA that suggests a mechanism for replication? Think about this for a minute, and then discuss it with your neighbor.
Data analysis and interpretation	Based on the data shown in this slide, researchers concluded that *Snarticus inferensis* is the causal agent of the disease.	Consider these data from the experiment I just described. Which of the following conclusions can you draw from them? Think about it for a minute, and then let's take a vote and discuss the results.
Biology and society	Many people have concerns about genetically modified organisms (GMOs). Some of these concerns are sell founded, and others are not. You have to decide for yourself	I'd like to split the class into two groups. One group will brainstorm about the potential of GMOs for beneficial purposes and the other about possible harmful consequences. Then we'll have a debate.

FIGURES



6. Evaluation: think critically about and defend a position
   Judge, Justify, Defend, Criticize, Evaluate
5. Synthesis: transform, combine ideas to create something new
   Develop, Create, Propose, Design, Invent
4. Analysis: break down concepts into parts
   Compare, Contrast, Distinguish
3. Application: apply comprehension to unfamiliar situations
   Apply, Use, Diagram, Compute, Solve, Predict
2. Comprehension: demonstrate understanding of ideas, concepts
   Restate, Explain, Summarize, Interpret, Describe
1. Factual Knowledge: remember and recall factual information
   Define, List, State, Name, Cite

Fig. 1

Standard course planning	**vs**	**Backward design**
Choose textbook		Formulate broad learning goals
⇓		⇓
Create syllabus		Set specific learning objectives
⇓		⇓
Write/revise lectures, notes, prepare PowerPoint presentations		Design assessments (formative and summative)
⇓		⇓
Write homework, exam questions		Prepare learning activities
Instructor-centered		**Student-centered**

Fig. 2

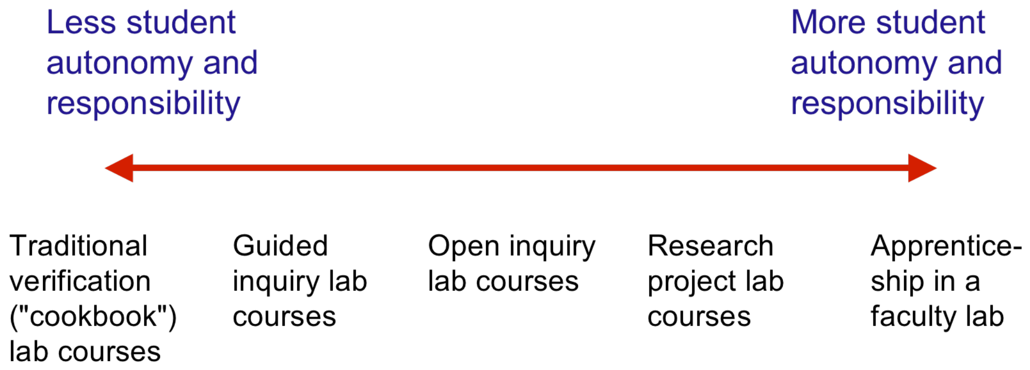

Less student autonomy and responsibility
More student autonomy and responsibility
Traditional verification ("cookbook") lab courses
Guided inquiry lab courses
Open inquiry lab courses
Research project lab courses
Apprenticeship in a faculty lab

Fig. 3