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Essay

How Can We Improve Problem Solving in Undergraduate Biology? Applying Lessons from 30 Years of Physics Education Research

A.-M. Hoskinson,* M. D. Caballero,† and J. K. Knight‡

*Department of Ecology and Evolutionary Biology, †Department of Physics, and ‡Department of Molecular, Cellular, and Developmental Biology, University of Colorado–Boulder, Boulder, CO 80309

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If students are to successfully grapple with authentic, complex biological problems as scientists and citizens, they need practice solving such problems during their undergraduate years. Physics education researchers have investigated student problem solving for the past three decades. Although physics and biology problems differ in structure and content, the instructional purposes align closely: explaining patterns and processes in the natural world and making predictions about physical and biological systems. In this paper, we discuss how research-supported approaches developed by physics education researchers can be adopted by biologists to enhance student problem-solving skills. First, we compare the problems that biology students are typically asked to solve with authentic, complex problems. We then describe the development of research-validated physics curricula emphasizing process skills in problem solving. We show that solving authentic, complex biology problems requires many of the same skills that practicing physicists and biologists use in representing problems, seeking relationships, making predictions, and verifying or checking solutions. We assert that acquiring these skills can help biology students become competent problem solvers. Finally, we propose how biology scholars can apply lessons from physics education in their classrooms and inspire new studies in biology education research.

INTRODUCTION

In 2009, more than 85,000 students earned undergraduate biology degrees at colleges and universities in the United States. These students represent the second-largest single population of science majors at American colleges and universities, trailing only psychology (National Science Board, 2012). Furthermore, in 2009, of the ~74,000 students enrolling for the first time in science graduate programs, 40% were in biology or medical-related fields (National Science Board, 2012), in which a strong foundation in solving problems will facilitate their success (National Academy of Science [NAS], 2011). Whether or not students graduating with a bachelor's degree in biology go on to use biology in their professions, they will undoubtedly confront complex problems as citizens: making medical decisions, engaging in conservation planning, and understanding climate change. Thus, no matter what their future careers, it is paramount that students in the biological sciences become capable of grappling with complex problems (American Association for the Advancement of Science [AAAS], 2011).

Based on introductory science enrollments, biology is likely the undergraduate discipline in which most students are first exposed to *scientific process skills*, such as developing hypotheses, interpreting data, crafting evidence-based arguments, and using and evaluating models of systems (National Science Board, 2012). These process skills are called *scientific practices* in much of the physics education literature and in the forthcoming *K–12 Next Generation Science Standards* (National Research Council [NRC], 2012b; www.nextgenscience.org). Helping students learn such skills facilitates their development

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Address correspondence to: A.-M. Hoskinson (annemarie.hoskinson@colorado.edu).

into competent problem solvers and exposes them to how scientists think about complex ideas in their disciplines (Dunbar, 2000; Taconis *et al.*, 2001). If students are to be successful in such problem solving later in life, they need to have extensively practiced such skills in their undergraduate science classes (AAAS, 2011; Jonassen, 2011; NAS, 2011).

The phrase "problem solving" appears regularly in the biology education research (BER) literature, and there is near-universal agreement that problem solving is a valuable skill for biology students to learn and practice (AAAS, 2011; NAS, 2011). Research about defining relevant biology problems, how students solve biology problems, and what conceptual knowledge they employ while solving biology problems is still in its formative stages. Furthermore, developing effective biology curricula that incorporate problem solving will depend on the outcome of such research (AAAS, 2011; NRC, 2012a). To help direct the future of problem solving in biology, BER scholars can gain insight from the work in other discipline-based education research (DBER) fields—namely, physics education research (PER).

PER scholars have investigated problem solving in physics for the past three decades (Hsu *et al.*, 2004), defining problems (Heller and Reif, 1984), investigating how students solve problems (Larkin *et al.*, 1980), exploring the role of conceptual knowledge in solving problems (Reif, 2008), and developing pedagogical and curricular tools that facilitate deeper learning (Heller and Hollabaugh, 1992; Mestre *et al.*, 1993; Pawl *et al.*, 2009). Historically, such research has concentrated on developing students' abilities to grapple with end-of-chapter physics problems by focusing student attention first on analysis of the underlying physics principles (i.e., *conceptual knowledge*). This work has spanned levels of instruction from middle and high school courses to upper-division undergraduate courses, has helped to improve student conceptual knowledge (Kohlmyer *et al.*, 2009), and, in some cases, has resulted in the development of research-based teaching practices in problem solving (Heller and Hollabaugh, 1992; Heller *et al.*, 1992). More recently, the PER community has found that by emphasizing scientific practices (*process skill*s in BER) in both curricula and pedagogy, gains in problem-solving competency can be achieved (Hestenes, 2000). The PER community has broadened the definition of problem solving to include employing aspects of professional science, for example, using conceptual knowledge to design experiments, develop and test models, and critique scientific information (Meltzer and Thornton, 2012).

In this paper, we discuss research-based approaches, first developed by PER scholars, that can be used by biologists to increase student problem-solving mastery and to inform future research into problem solving in biology. By contrasting authentic, complex problems with the kinds of problems that biology students are typically asked to solve (see the following section), we illuminate a significant gap between existing curricular methods and the professional practices of biologists. We summarize the work done by PER scholars that narrowed a similar gap between physics education and the practice of physics in *Narrowing the Course Work–Practice Gap in Physics*. We conclude with a discussion of how biology educators can put lessons from PER into practice, and suggest new directions for research into biology problem-solving theory and practice (see *How Can PER Inform BER on Problem Solving?).*

UNDERGRADUATE BIOLOGY AND COMPLEX PROBLEMS: A COURSE WORK–PRACTICE GAP

There are many ways to describe problem-solving processes. Here, we focus on problems and problem-solving strategies. When biology researchers investigate a topic, they engage in a variety of scientific practices that are routine for scientists, but often difficult for students: these are authentic and complex problems (Chi, 2005; AAAS, 2011). Problem-solving activities designed for students can be characterized along two axes: by the *content* and *structure* of the problems to be discovered and solved; and by the *process skills* or *scientific practices* that problem solvers must engage in to achieve a solution (Table 1; Fischer and Greiff, 2012).

The phrase "authentic problem" has multiple meanings in BER, including real-world problems (Jonassen, 2011; Gormally *et al.*, 2012), problems with personal and social relevance (Hanauer *et al.*, 2006; Wenglinsky and Silverstein, 2007), and problems with multiple possible solutions (Steen, 2005; AAAS, 2011; Brownell *et al.*, 2011). Likewise, "complexity" has both colloquial and discipline-specific meanings. However there is good alignment about what constitutes a complex problem, whether in physics or biology (Goldenfeld, 1999; Fischer and Greiff, 2012). First, complex problems often explore systems and phenomena that are dynamic, nonlinear, stochastic, and/or emergent (e.g., interactions among gene sequences, probabilistic mutations, and chromosomal segregation in inheritance; interactions among animals, plant, climate, nutrients, etc., in a watershed; the relevant model needed to design a working catapult; Table 1, D–F). Complex problems have multiple elements, features, or variables of the system that must be considered (i.e., the elements of inheritance include gene sequences, mutation sites, enzymes, and chromosomes; the elements of an ecosystem include organisms, environment, and nutrients; the elements of dynamics include force, acceleration, velocity, and position). The elements have variable relationships with one another that are not necessarily defined in the problem description (i.e., the relationships between genes and their expression is moderated by probabilistic mutation and gene regulation; the relationship between elements of urban streams is driven by intra- and interannual climate variation; the relationships governing motion are Newton's Second Law and kinematics).

Complex problems can also be considered in terms of how the problem solver must interact with the problems by using particular skills and practices. Unlike routine problems, or exercises (Smith and Good, 1984), complex problems cannot be solved merely by recalling facts from memory or by using a simple algorithm. Instead, complex problems require that problem solvers engage in a wider variety of scientific practices—processes and skills specifically defined as complex problem solving (CPS) in the literature (Frensch and Funke, 1995; Jacobson, 2001; Fischer *et al.*, 2012). This second aspect of problem solving emphasizes the levels of cognitive functioning or expert-like skills necessary for solving the problem. Problems that involve scientific practices, such as analyzing data, evaluating outcomes, employing conceptual knowledge, and designing experiments, require higher levels of cognitive functioning than exercises that require merely recalling simple facts (Bloom, 1956).

In addition to the higher levels of cognitive functioning needed, CPS requires that problem solvers characterize

Table 1. Attributes of problem solving characterized by features of the problem and skills required, with several examples of simple problems or exercises (A–C) and complex problems (D–F) illustrating the distinct features of simple and complex problems

		Problem features			Process skills (practices)	
	Example problem	Elements	Relationships	Solutions	Lower-order cognitive skills required	Higher-order cognitive skills required
A. Simple genetics exercise	Cystic fibrosis is an autosomal recessive disease. If two individuals who are both carriers of the same cystic fibrosis mutation have a child together, what is the probability that their child will be a carrier?	Alleles, chromosome segregation, probability	Deterministic probability	One	Recall facts about inheritance and probability Solve the equation	Turn a verbal representation into an equation
B. Simple ecology exercise	Given a current population size and intrinsic growth rate, predict a future population size.	Population size, growth rate	Deterministic	One	Recall facts about population growth Solve the equation	Turn a verbal representation into an equation
C. Simple physics exercise	An object is thrown horizontally with a speed of 20 m/s from a 40-m-high tower. How far from the base of the tower does the object land?	Position, velocity, acceleration	Deterministic	One	Define terms Solve the equation	Turn a verbal representation into an equation
D. Complex genetics problem	Using data from cystic fibrosis (CF) gene sequencing, restriction digest sites, and mutation probabilities, predict whether babies born to CF carrier parents will have CF or be carriers, and propose how to explain your prediction to parents.	Alleles, chromosome segregation, probabilities, use of restriction digest sites for analysis of DNA sequences, output of molecular analysis	Stochastic Probabilistic Emergent: analysis of molecular data	Many	Recall facts about inheritance and probability Solve the equation	Analyze relationships Reduce and filter information Refine ambiguous goal states Synthesize data Evaluate evidence Argue from evidence Reflect on goal state and progress
E. Complex ecology problem	Devise a management strategy among multiple stakeholders for a small urban watershed to maximize water diversion and catchment, recreation, species preservation, and water quality.	Multiple stakeholders, biodiversity, water quality metrics, catchment volume	Dynamic Emergent: intra- and interannual rainfall variation, precipitation duration, timing, intervals, species responses, stakeholder investments	Many	Recall facts about population growth Solve the equation	Analyze relationships Reduce and filter information Refine ambiguous goal states Synthesize data Evaluate evidence Argue from evidence Reflect on goal state and progress
F. Complex physics problem	Design a catapult that ejects a watermelon such that it passes through the uprights of a field goalpost.	Catapult and elastic, watermelon, air/wind variables	Deterministic	Many	Define terms Solve the equation	Build a model Evaluate evidence Argue from evidence Reflect on goal state and progress

problems in expert-like ways. Expert problem solvers and novices are known to differ both in their characterizations of complex problems (Chi and Slotta, 1994; Jacobson, 2001) and in the processes, methods, and skills each group uses to solve them. Novices are more likely to attribute external control to complex systems and to focus on stepwise solutions. Experts acknowledge attributes of complex systems, such as emergence and stochasticity (Chi *et al*., 1981; Chi, 2008). Experts also seek multiple solution pathways (Taconis *et al*., 2001), use more sophisticated heuristics (Nicolson *et al*., 2002; Fischer and Greiff, 2012), and employ cognitive flexibility and filtering (DeHaan, 2009) to reduce both solution space and potential solution pathways (Table 1).

Many biologists agree that students should learn to solve biology problems requiring complex problem-solving skills (Taconis *et al*., 2001; Jonassen, 2011). Often, though, the problems students solve in biology classes are simple exercises in which the system is well understood, most or all variables and relationships are given, a solution path (algorithm) is given or known, and the solution or answer is predefined. Consider an example of an exercise many genetics students work through (Table 1A). In this case, the system—chromosomal inheritance—is well understood. All of the variables are given, and there is one correct way to calculate the single correct answer. Similar examples abound in other domains of biology (Table 1B) and in physics (Table 1C).

Alternatively, consider the kinds of problems that scientifically literate citizens should be able to solve (Table 1, D–F). In these problems and many others, the understanding of the system is vague or may not be shared among the problem solvers. This can lead to multiple, potentially competing ideas of what constitutes a solution or answer (Nicolson *et al*., 2002; Fischer and Greiff, 2012). The representations of both problem elements and relationships among the elements are poor (Jonassen, 2011; Fischer and Greiff, 2012). As the number of elements and relationships increases, their interdependence makes simpler problem representations and paper-and-pencil solutions by single individuals less feasible. Consequently, cooperation among multiple people—population ecologists, environmental chemists, economists, politicians, and citizens—may be required to adequately represent and solve the problem (Table 1, D and E). The need for communication among experts and nonexperts may also be featured (Table 1, D and E).

To solve these authentic, complex problems, participants engage in a wider variety of scientific practices than when solving simple exercises. These kinds of problems are infrequently presented in most of undergraduate biology curricula; thus, there remains a significant gap between the kind of problems students can solve and the kind of problems they should be able to solve.

NARROWING THE COURSE WORK–PRACTICE GAP IN PHYSICS

Over the past 30 years, physics education researchers have investigated how students learn to solve problems in physics courses through a variety of perspectives (McDermott and Redish, 1999; Hsu *et al*., 2004). This work has lead to a substantial number of research-based curricular and pedagogical tools that improve student learning in physics (Meltzer and Thornton, 2012). Despite significant strides made by PER, many researchers and instructors are just now beginning to make use of authentic, complex problems. There is still much work to be done in PER to describe what authentic and complex physics problems look like, how students engage in scientific practices when solving such problems, and how students who learn to solve authentic and complex physics problems perform on more traditional assessments of problem solving.

Early work in PER highlighted the substantial differences between how physics students and experts think about the nature of science, including how their knowledge of physics principles is organized and used and what practices they employ to solve physics problems (Chi *et al*., 1981, 1989; Reif, 2008). Representative problems were typical exercises. This research illuminated how students could successfully solve exercises without conceptual knowledge of the underlying physics.

Unlike novice students, physics experts rarely begin solving problems by using mathematical equations. Just as in the biological sciences, physics experts often think of a few governing principles and heuristics and then construct models to make sense of physical phenomena. Often, they begin with their conceptual knowledge of the problem and then develop it to include mathematical representations. Further refinement and mathematical manipulations lead to appropriate expressions of the problem (Reif, 2008).

Novices, on the other hand, often think of physics as a loose collection of ideas and equations with few or no connections among them (Chi *et al*., 1981). When solving exercises, students rarely employ their conceptual knowledge, preferring instead to hunt for equations that contain all the elements (e.g., velocity, acceleration, mass) given in the problem statement (Chi *et al*., 1989; Reif, 2008). Practices such as equation hunting emphasize memorization strategies that facilitate students' strong performance on traditional exams, which are typically constructed from exercises. Traditional exams tend to reward finding a single solution to an exercise (answer making) rather than demonstrating a deep understanding of principles and methods (sense making; McDermott and Redish, 1999; Meltzer and Thornton, 2012).

Early work in PER demonstrated that, in addition to applying conceptual knowledge to solve exercises, students need to learn to construct a variety of representations of physical systems, to coordinate between those representations, and to execute the necessary mathematics to successfully solve problems in physics. While this early work did not seek to define the authenticity or complexity of problems per se, it did provide the necessary foundation for researchers and instructors to develop transformative teaching methods. By emphasizing a number of scientific practices that were not present in traditional lecture courses, teaching methods emphasized authentic problems. For example, when a standard exercise is reframed as a design activity (Table 1F), students must confront how a problem is defined, how a model can be constructed, and how variables can be reduced, so the problem can be solved using the elementary physics and mathematics they are learning.

Building on the work of Chi, McDermott, Reif, and others, Heller and colleagues formalized the tasks needed for solving typical exercises into a coherent framework (Heller and Heller, 1995). In one instantiation of this framework, Heller and colleagues developed a suite of authentic problems not typically represented in physics curricula. While these problems were not necessarily complex (they still resolved to a single solution), they were authentic (*context-rich* in Heller and Heller [1995], or real-world scenarios, often with personal relevance). These problems provided students with real-world scenarios ("you are a stunt driver jumping a series of buses") in which decisions had to be made about particular variables (e.g., mass of car + driver, initial velocity after leaving ramp) to facilitate a solution (e.g., landing safely). To solve these problems, students used a stepwise framework: 1) focus on the problem, 2) describe the physics, 3) plan the solution, 4) execute the plan, and 5) evaluate the answer. This framework makes explicit use of conceptual knowledge in steps 1 and 2 and connects that knowledge directly to representing the problem mathematically in step 3 (Heller and Heller, 1999).

In addition to using problems that were context-rich, Heller and Heller also made use of cooperative groups, which involved students in all aspects of the problem-solving process, offered opportunities for students to critique their peers' problem-solving practices, and facilitated the use of more challenging problems (Heller and Hollabaugh, 1992; Heller *et al*., 1992). Explicit teaching of problem-solving practices in this way (e.g., activating and employing conceptual knowledge early in the problem-solving process) helped students develop such skills more quickly, and these students performed better on qualitative exam questions than traditionally taught students (Foster, 2000).

Engaging students with context-rich problems in a cooperative group format is but one of a number of attempts by the PER community to develop students' abilities to solve problems in the traditional sense. In another example, O'Kuma and colleagues (2000) developed a series of ranking tasks to elicit student ideas about physical systems rather than memorized responses. The structure and content of such problems were not particularly authentic (e.g., limited personal or social relevance), but these tasks increased the complexity of usual course activities. Students attended to multiple elements in a single scenario (e.g., mass and velocity of a car), while considering the relationships within groups of elements and among scenarios (e.g., ranking car crash scenarios in order of the force experienced). Such tasks promoted both students' conceptual knowledge and their traditional problem-solving skills (O'Kuma *et al*., 2000). These tasks have been broadened to include a variety of alternative problem types and to engage students in more authentic scientific practice. Many of the newer activities require students to utilize their conceptual knowledge to explain their solutions to peers or to critique the solution offered by others (Hieggelke *et al*., 2006a,b). Others have leveraged alternative representations (verbal descriptions, diagrams, graphs, and equations) to focus novice problem solvers on performing a conceptual analysis by first coordinating between the different representations (Van Heuvelen and Maloney, 1999; Van Heuvelen and Zou, 2001)

More recently, PER has begun work at the upper-division undergraduate level, in which course goals and the activities pursuing those goals are significantly more complex (e.g., using and connecting more sophisticated mathematical and physical ideas). For typical upper-division problems, students often grapple with complex systems in addition to considering how multiple elements and their relationships facilitate a solution (e.g., using the calculus of variations to determine Snell's law). Moreover, students in upper-division physics become acculturated to the scientific practices of professional physicists (e.g., developing and using models, gathering evidence, evaluating outcomes). Despite the increasing complexity of these problems, many upper-division physics problems are still inauthentic (idealized models of systems with limited personal relevance), and upper-division students struggle to solve these problems (Pepper *et al*., 2012). To uncover why students struggle, Caballero and colleagues developed a framework that has been used to analyze how students solve problems in upper-division physics courses (Caballero *et al*., 2013; Wilcox *et al*., 2013). Their work investigates how students blend their conceptual knowledge with problem-solving practices to achieve solutions. Preliminary findings show that these physics students' primary difficulties include constructing precise models and evaluating the appropriateness of solutions. These scientific practices are two that professional physicists use daily, and students' difficulties with these practices must be addressed to strengthen their professional preparation.

While the previous examples of research-based tools emphasized, to various degrees, either authentic or complex problems, physics teaching that focuses on developing students' ability to engage in scientific practice tends to use both. In physics, scientific practices include constructing and evaluating models, designing and executing experiments, and engaging in argumentation based on evidence. Scientific practices underpin what it means to engage in complex problem solving; in fact, these are the practices that professional scientists use to solve challenging problems in their own work (NRC, 2012a). Through this lens, recent reforms in introductory physics have broadened the traditional definition of problem solving to include engaging in the practices of professional science. Consider again the design problem posed in Table 1F; such a problem engages students in the practice of science and thus can be characterized as an authentic and complex problem.

There are a number of curricular examples that emphasize scientific practices, and, hence, this broader definition of problem solving, such as Workshop Physics (Laws, 1991; Etkina and Van Heuvelen, 2007). Modeling Instruction (Hestenes, 1987) is another approach gaining wider acceptance both in PER and the broader physics community. Modeling Instruction is worth describing in some detail because it has been implemented in both high school (Hestenes *et al*., 1995) and university (Brewe, 2008) settings. Moreover, ~10% of the nation's high school physics teachers have had some formal training in Modeling Instruction.

Modeling Instruction uses a theoretical framework (the modeling cycle) around which student activities are organized. Students engage in open-ended experimental and theoretical procedures while making real-world observations and then propose possible measurements that can help describe observed patterns. From these measurements, students observe trends and patterns that help to inform their development of representative models. They then test their models against additional observations to evaluate their models' capacity to explain the observed phenomena. Students subsequently repeat this observation–development–evaluation cycle for new phenomena. Through this cycle, students discover the necessary elements and their relationships that describe the observed system. While the physics and mathematics are not particularly complex, students utilize several scientific practices during a single cycle: developing and using models, finding patterns, testing hypotheses. The Modeling Instruction curriculum is demonstrably effective in teaching physics concepts (Hestenes, 2000), developing students' self-efficacy (Sawtelle *et al*., 2010), enriching their notions about the nature of science (Brewe *et al*., 2009), and improving students' traditional problem-solving competence (Malone, 2008). Both Workshop Physics and Investigative Science Learning Environment (ISLE) are similarly organized, with slightly differing pedagogies but equally effective results (Redish and Steinberg, 1999; Etkina, 2006). Physics courses that emphasize scientific practices will likely serve students well in their future course work and beyond.

While many teaching methods have been developed by the PER community, effectiveness is often evaluated using end-of-course conceptual assessments. Concept inventories (assessments) measure whether students can show evidence of deeper learning from particular instructional strategies (Hestenes *et al*., 1992; Beichner, 1994; Ding *et al*., 2006). Through measuring student-learning gains, these assessments have demonstrated the benefits of using active-engagement scientific practices in teaching (Hake, 1998; Hestenes, 2000; Pollock and Finkelstein, 2013). Concept inventories have also been used to quantify the outcomes of introductory and upper-division physics courses (Kohlmyer *et al*., 2009; Caballero *et al*., 2012; Chasteen *et al*., 2012). Despite their value, most physics concept inventories do not directly measure problem solving—even as narrowly defined. Thus, they may or may not serve well as predictors of such skills in students. One instrument that begins to characterize students' problem-solving skills in exercises is the Mechanics Baseline Test (MBT; Hestenes and Wells, 1992). However, this instrument cannot directly evaluate authentic scientific practice skills, because the MBT's multiple-choice format is not amenable to investigating how students employ scientific practices. Future work in PER is needed to assess how students employ scientific practices.

HOW CAN PER INFORM BER ON PROBLEM SOLVING?

Theoretically, biologists should be able to apply the approaches that physics education researchers have found successful in improving instruction and student learning, especially because some of the same scientific practices have already been identified as critical in biology (e.g., formulating hypotheses, gathering and evaluating evidence, and using evidence to construct arguments). However, biology education researchers are still working to define what it looks like for students to solve complex problems in biology. We focus below on ways in which the findings on problem solving in PER can specifically impact curriculum development and research on problem solving in biology.

Problem Solving in the Biology Classroom

New curricula for biology students should include ways for students to use scientific practices and process skills and to engage in complex problem solving, as described above. Currently, many problems that biology students are asked to solve are exercises. Consider an exercise that a biology student might encounter in an introductory genetics course: calculating inheritance probabilities of sex-linked traits. A problem on this topic could be presented as follows:

> Suppose that hemophilia is an X-linked recessive trait. If a mother is a carrier for hemophilia, and the father is normal, what is the chance that their son will have hemophilia?

To make the problem more complex and engage students in more authentic problem-solving practices, the prompt can emphasize the construction (design) of a possible pedigree, such as:

> Generate a possible pedigree for three generations showing unaffected, affected, and carrier individuals in a pedigree for hemophilia. Share your pedigree with your neighbor. How are the two pedigrees different? Which is more likely to occur, given the history of hemophilia?

This approach (as well as the other examples included in Table 1) transforms a typical exercise into a complex problem, inviting students to generate possible scenarios by applying their knowledge of a generalized system (chromosomal inheritance) to a specific application.

Such problems could also be presented to students as in-class concept clicker questions. In the peer instruction model originally proposed by Mazur (1997), multiple-choice in-class questions can be used to foster discussion among students, engaging them in a community of problem solvers. Clickers work well for implementing this active-learning technique in both biology and physics, because they are easy to incorporate, especially in large classes, and they can provide immediate feedback to both students and instructor (Wood, 2004). Some may view multiple-choice clicker questions as limited, because the potential answers are defined; however, it is possible to write multiple-choice questions that require higher-order thinking and that require students to engage in complex problem solving (Crowe *et al*., 2008). Curricula that encourage the use of complex problem solving in class, as practices or as part of formative assessment, have the potential to foster complex problem-solving abilities in students (DeHaan, 2009; Maskiewicz *et al*., 2012)

The observation–development–evaluation cycle of Modeling Instruction could also be adapted to biological problems and implemented in a variety of classroom settings. Some biology resources already exist that could be adapted for this purpose, such as case studies (National Center for Case Study Teaching in Science, 2012; Ecological Society of America, 2013) and problem-based scenarios (Norman and Schmidt, 2000). These examples begin with authentic, catchy stories to pique students' interest, usually describing observations from the viewpoint of science students rather than expert scientists (personal relevance). Then, students develop experiments to test hypotheses, to explore the sensitivity of a model to changes in variables or parameters, or to suggest and justify what further measurements they would make (authentic scientific practice). The final step in case-based or problem-based curricula is to evaluate evidence against observations and to construct arguments for a resolution to a problem or dilemma. This kind of curricular path, then, builds in higher-order process skills that support student problem solving.

Following the work of PER scholars who introduced the importance of measuring conceptual understanding and sense-making with concept inventories (e.g., Hestenes *et al.*, 1992), biologists have recently developed a variety of such assessments in different subdisciplines of biology (D'Avanzo, 2008). Not all concept inventories have been developed with attention to evidence of validity and reliability (Huffman and Heller, 1995), and few directly measure problem-solving or critical-thinking skills (Smith and Tanner, 2010), as also described above. Nonetheless, several of the most recently developed biology concept inventories/assessments have demonstrated utility in uncovering concepts for which students have persistent difficulties (Garvin-Doxas and Klymkowsky, 2008; Parker *et al.*, 2012; Smith and Knight, 2012). In addition, several recently developed assessments are devoted at least in part to specifically measuring problem solving (i.e., diagnostic question clusters [DQC]; Parker *et al.*, 2012), critical thinking (Bissell and Lemons, 2006), and basic process skills (Gormally *et al.*, 2012). In fact, assessing how students engage in scientific practices is important to all DBER communities (NRC, 2012a). Student performance on these kinds of tools, coupled with the results of formative assessments devoted to problem solving, may be useful in further informing curricular change.

Research

Though gaps between theory and practice remain, these gaps also suggest rich opportunities for research. For instance, as described in *Undergraduate Biology and Complex Problems: A Course Work–Practice Gap*, some BER scholars have begun to investigate how student conceptions of biological principles and processes differ from those of experts. One approach to solidifying our understanding of biological problem solving would be to ask what process skills novices tend to employ when problem solving, and compared those with skills that experts typically employ. Similar investigations were helpful in framing the development of research-based instructional materials for introductory physics courses (McDermott and Shaffer, 2002). An understanding of the processes that expert biologists use to solve problems could be used to help teach the scaffolding of both content knowledge and process skills to students. Process skills may also be an important mechanism linking problem-solving activity and conceptual knowledge.

Although there exist ways of measuring some aspects of problem solving, and other methods to assess conceptual knowledge, there have been few investigations of ways to measure conceptual knowledge using the processes of problem solving (Nehm, 2010). DQCs (Parker *et al.*, 2012) and Bissell and Lemons' (2006) methods are encouraging steps toward establishing and exploring these links. Work that explores the kinds of links between conceptual knowledge and sense making with actual problem solving competence should also focus on developing assessments that are validated and easy to deploy.

One important difference between physics and biology lies in how problems represent systems behavior. Physics problems tend to emphasize quantitative representations. Qualitative, conceptual, and pictorial representations are used extensively in physics, but, ultimately, the goal of many problems is to connect the physics to the mathematics to make predictions. Whether simple or complex, such problems require the problem solver to use quantitative representations, such as equations, graphs, or predictive models. While some biological problems are quantitative, many others rely upon different representations, including diagrammatic or pictorial representations, such as those used to represent signaling pathways, biological cycles, or relationships among cycles (i.e., life, carbon, nutrients, populations). A few studies have investigated how students perceive and interpret the representations drawn by experts (Schönborn and Anderson, 2009), and how such representations can introduce and perpetuate misconceptions (Catley and Novick, 2008), but there is relatively little work on how students generate their own representations (Kose, 2008), or how their representations impact their problem-solving skills.

Understanding and coordinating between representations is but one distinguishing feature and promising area of research into complex problem solving in biology. Other process skills may be just as necessary and important for biology students to learn. Metacognition is widely recognized as important for learning (Tanner, 2012), and it may be especially important in CPS for progress checking and for reconciling feedback among potential solutions, representations, and mental models. Decision making as a process skill may also be fundamental to CPS (Nicolson *et al.*, 2002; Fischer and Greiff, 2012).

Although we have identified several structures and processes common to complex problem solving, this is by no means a comprehensive list or an operational model for designing problems or assessing problem solving. The development of operational models of CPS processes would help target the behaviors and skills necessary for students to engage in solving authentic, complex problems in the classroom and in their lives. We live at a time when complex biological problems are not just the realm or responsibility of highly trained scientists. The people who are currently our students will need to engage along with us as citizens once they leave college. Thus, it serves all of us to engage in solving the kinds of problems that will emerge in our collective futures.

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REFERENCES

American Association for the Advancement of Science (2011). Vision and Change in Undergraduate Biology Education: A Call to Action, Washington, DC.

Beichner RJ (1994). Testing student interpretation of kinematics graphs. Am J Phys *62*, 750–762.

Bissell AN, Lemons PP (2006). A new method for assessing critical thinking in the classroom. BioScience *56*, 66–72.

Bloom BS (1956). Taxonomy of Educational Objectives, Handbook I: The Cognitive Domain, New York: David McKay.

Brewe E (2008). Modeling theory applied: Modeling Instruction in introductory physics. Am J Phys *76*, 1155.

Brewe E, Kramer L, O'Brien G (2009). Modeling Instruction: positive attitudinal shifts in introductory physics measured with CLASS. Phys Rev Spec Top Phys Educ Res *5*, 013102.

Brownell SE, Kloser MJ, Fukami T, Shavelson R (2011). Undergraduate biology lab courses: comparing the impact of traditionally-based "cookbook" and authentic research-based courses on student lab experiences. J Coll Sci Teach *41*, 36–45.

Caballero MD, Greco EF, Murray ER, Bujak KR, Jackson Marr M, Catrambone R, Kohlmyer MA, Schatz MF (2012). Comparing large lecture mechanics curricula using the Force Concept Inventory: a five thousand student study. Am J Phys *80*, 638.

Caballero MD, Wilcox BR, Pepper RE (2013). ACER: a framework on the use of mathematics in upper-division physics. In: 2012 Physics Education Research Conference, AIP Conference Proceedings vol. 1513, New York: AIP, 90–93.

Catley KM, Novick LR (2008). Seeing the wood for the trees: an analysis of evolutionary diagrams in biology textbooks. BioScience *58*, 976–987.

Chasteen S, Pepper RE, Caballero MD, Pollock SJ, Perkins K (2012). Colorado Upper-Division Electrostatics Diagnostic: a conceptual assessment for the junior level. Phys Rev Spec Top Phys Educ Res *8*, 020108.

Chi M (2005). Commonsense conceptions of emergent processes: why some misconceptions are robust. J Learn Sci *14*, 161–199.

Chi M (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In: Handbook of Research on Conceptual Change, ed. S Vosniadou, Hillsdale, NJ: Lawrence Erlbaum, 61–82.

Chi M, Slotta J (1994). From things to processes: a theory of conceptual change for learning science concepts. Learn Instr *4*, 27–43.

Chi MTH, Bassok M, Lewis MW, Reimann P, Glaser R (1989). Self-explanations: how students study and use examples in learning to solve problems. Cogn Sci *13*, 145–182.

Chi MTH, Feltovich PJ, Glaser R (1981). Categorization and representation of physics problems by experts and novices. Cogn Sci *5*, 121–152.

Crowe A, Dirks C, Wenderoth MP (2008). Biology in Bloom: implementing Bloom's taxonomy to enhance student learning in biology. CBE Life Sci Educ *7*, 368–381.

D'Avanzo C (2008). Biology concept inventories: overview, status, and next steps. BioScience *58*, 1–7.

DeHaan RL (2009). Teaching creativity and inventive problem solving in science. CBE Life Sci Educ *8*, 172–181.

Ding L, Chabay R, Sherwood B, Beichner R (2006). Evaluating an electricity and magnetism assessment tool: brief electricity and magnetism assessment. Phys Rev Spec Top Phys Educ Res *2*, 010105.

Dunbar K (2000). How scientists think in the real world: implications for science education. J Appl Dev Psychol *21*, 49–58.

Ecological Society of America (2013). EcoEd Digital Library. http://ecoed.esa.org/index.php?P=Home (accessed 19 February 2013).

Etkina E (2006). Scientific abilities and their assessment. Phys Rev Spec Top Phys Educ Res *2*, 020103.

Etkina E, Van Heuvelen A (2007). Investigative science learning environment—a science process approach to learning physics. In: Research-Based Reform of University Physics, ed. EF Redish and PJ Cooney, College Park, MD: American Association of Physics Teachers.

Fischer A, Greiff S, Funke J (2012). The process of solving complex problems. J Prob Solv *4*, 19–42.

Foster TM (2000). The development of students' problem-solving skill from instruction emphasizing qualitative problem-solving. PhD Thesis, Minneapolis: University of Minnesota.

Frensch PA, Funke J (1995). Definitions, traditions, and a general framework for understanding complex problem solving. In: Complex Problem Solving: The European Perspective, ed. PA Frensch and J Funke, Hillsdale, NJ: Lawrence Erlbaum, 3–26.

Garvin-Doxas K, Klymkowsky MW (2008). Understanding randomness and its impact on student learning: Lessons learned from building the Biology Concept Inventory (BCI). CBE Life Sci Educ *7*, 227–233.

Goldenfeld N (1999). Simple lessons from complexity. Science *284*, 87–89.

Gormally C, Brickman P, Lutz M (2012). Developing a Test of Scientific Literacy Skills (TOSLS) in biology: measuring undergraduates' evaluation of scientific information and arguments. CBE Life Sci Educ *11*, 364–377.

Hake R (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.

Hanauer DI, Jacobs-Sera D, Pedulla ML, Cresawn SG, Hendrix RW, Hatfull GF (2006). Teaching scientific inquiry. Science *314*, 1880–1881.

Heller JI, Reif F (1984). Prescribing effective human problem-solving processes: problem description in physics. Cogn Instr *1*, 177–216.

Heller P, Heller K (1995). The Competent Problem Solver: A Strategy for Solving Problems in Physics, Minneapolis, MN: McGraw-Hill.

Heller P, Heller K (1999). Cooperative Group Problem Solving in Physics, Minneapolis: University of Minnesota. http://groups.physics.umn.edu/physed/Research/CGPS/Green%20Book/cover_tc.pdf.

Heller P, Hollabaugh M (1992). Teaching problem solving through cooperative grouping. Part 2: designing problems and structuring groups. Am J Phys *60*, 637–644.

Heller P, Keith R, Anderson S (1992). Teaching problem solving through cooperative grouping. Part 1: group versus individual problem solving. Am J Phys *60*, 627–636.

Hestenes D (1987). Toward a modeling theory of physics instruction. Am J Phys *55*, 440–454.

Hestenes D (2000). Findings of the Modeling Workshop Project, 1994–2000, Tempe: Arizona State University. http://modeling.asu.edu/R&E/ModelingWorkshopFindings.pdf.

Hestenes D, Wells M (1992). A mechanics baseline test. Phys Teach *30*, 159–166.

Hestenes D, Wells M, Swackhamer G (1992). Force Concept Inventory. Phys Teach *30*, 141–158.

Hestenes D, Wells M, Swackhamer G (1995). A modeling method for high school physics instruction. Am J Phys *63*, 606–619.

Hieggelke C, Maloney D, Kanim S (2006a). Newtonian Tasks Inspired by Physics Education Research: nTIPERs, Boston, MA: Addison-Wesley.

Hieggelke C, Maloney D, Kanim S, O'Kuma T (2006b). E&M TIPERs: Electricity and Magnetism Tasks Inspired by Physics Education Research, Upper Saddle River, NJ: Pearson, Prentice Hall.

Hsu L, Brewe E, Foster TM, Harper KA (2004). Resource letter RPS-1: research in problem solving. Am J Phys *72*, 1147–1156.

Huffman D, Heller P (1995). What does the Force Concept Inventory actually measure? Phys Teach *33*, 138–143.

Jacobson M (2001). Problem solving, cognition, and complex systems: differences between experts and novices. Complexity *6*, 41–49.

Jonassen D (2011). Designing for problem solving. In: Trends and Issues in Instructional Design and Technology, ed. R Reiser and J Dempsey, Boston, MA: Pearson Education, 64–74.

Kohlmyer M, Caballero M, Catrambone R, Chabay R, Ding L, Haugan M, Marr M, Sherwood B, Schatz M (2009). Tale of two curricula: the performance of 2000 students in introductory electromagnetism. Phys Rev Spec Top Phys Educ Res *5*, 020105.

Kose S (2008). Diagnosing student misconceptions: using drawings as a research method. World Appl Sci J *3*, 283–293.

Larkin J, McDermott J, Simon DP, Simon HA (1980). Expert and novice performance in solving physics problems. Science *208*, 1335–1342.

Laws PW (1991). Calculus-based physics without lectures. Phys Today *44*, 24.

Malone KL (2008). Correlations among knowledge structures, force concept inventory, and problem-solving behaviors. Phys Rev Spec Top Phys Educ Res *4*, 020107.

Maskiewicz AC, Griscom HP, Welch NT (2012). Using targeted active-learning exercises and diagnostic question clusters to improve students' understanding of carbon cycling in ecosystems. CBE Life Sci Educ *11*, 58–67.

Mazur E (1997). Peer Instruction: A User's Manual, Upper Saddle River, NJ: Prentice-Hall.

McDermott LC, Redish EF (1999). Resource letter PER-1: physics education research. Am J Phys *67*, 755–767.

McDermott LC, Shaffer PS (2002). Tutorials in Introductory Physics, Upper Saddle River, NJ: Prentice Hall.

Meltzer DE, Thornton RK (2012). Resource letter ALIP–1: active-learning instruction in physics. Am J Phys *80*, 478.

Mestre JP, Dufresne RJ, Gerace WJ, Hardiman PT, Touger JS (1993). Promoting skilled problem-solving behavior among beginning physics students. J Res Sci Teach *30*, 303–317.

National Academy of Science (2011). The Current Status and Future Direction of Biology Education Research, Washington, DC: National Academies of Science Press.

National Center for Case Study Teaching in Science (2012). National Center for Case Study Teaching in Science, Buffalo: State University of New York–Buffalo. http://sciencecases.lib.buffalo.edu/cs/ (accessed 19 February 2013).

National Research Council (NRC) (2012a). Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering, Washington, DC: National Academies of Science Press.

NRC (2012b). A Framework for K–12 Science Education: Practices: Crosscutting Concepts, and Core Ideas, Washington, DC: National Academies of Science Press.

National Science Board (2012). Science and Engineering Indicators 2012, Arlington, VA: National Science Foundation.

Nehm RH (2010). Understanding undergraduates' problem-solving processes. J Microbiol Biol Educ *11*, 119–122.

Nicolson CR, Starfield AM, Kofinas GP, Kruse JA (2002). Ten heuristics for interdisciplinary modeling projects. Ecosystems *5*, 376–384.

Norman GR, Schmidt HG (2000). Effectiveness of problem-based learning curricula: theory, practice, and paper darts. Med Educ *69*, 557–565.

O'Kuma T, Maloney D, Hieggelke C (2000). Ranking Tasks in Physics, Upper Saddle River, NJ: Prentice Hall.

Parker JM, Anderson CW, Heidemann M, Merrill J, Merritt B, Richmond G, Urban-Lurain M (2012). Exploring undergraduates' understanding of photosynthesis using diagnostic question clusters. CBE Life Sci Educ *11*, 47–57.

Pawl A, Barrantes A, Pritchard DE (2009). Modeling applied to problem solving. In: 2009 Physics Education Research Conference, AIP Conference Proceedings, vol. 1179, New York: AIP, 51–54.

Pepper RE, Chasteen S, Pollock SJ, Perkins K (2012). Observations on student difficulties with mathematics in upper-division electricity and magnetism. Phys Rev Spec Top Phys Educ Res *8*, 010111.

Pollock SJ, Finkelstein ND (2013). Impacts of curricular change: 8 years of conceptual survey data from introductory physics. In: 2012 Physics Education Research Conference, AIP Conference Proceedings, New York: AIP, 310–313.

Redish EF, Steinberg R (1999). Teaching physics: figuring out what works. Phys Today *52*, 24–31.

Reif F (2008). Applying Cognitive Science to Education, Cambridge, MA: MIT Press.

Sawtelle V, Brewe E, Kramer LH (2010). Positive impacts of modeling instruction on self-efficacy. In: 2010 Physics Education Research Conference, AIP Conference Proceedings, vol. 1289, New York: AIP, 289–292.

Schönborn KJ, Anderson TR (2009). A model of factors determining students' ability to interpret external representations in biochemistry. Int J Sci Educ *31*, 193–232.

Smith JI, Tanner K (2010). The problem of revealing how students think: concept inventories and beyond. CBE Life Sci Educ *9*, 1–5.

Smith M, Good R (1984). Problem-solving and classical genetics: successful versus unsuccessful performance. J Res Sci Teach *21*, 895–912.

Smith MK, Knight JK (2012). Using the Genetics Concept Assessment to document persistent conceptual difficulties in undergraduate genetics courses. Genetics *191*, 21–32.

Steen LA (ed.) (2005). Math & Bio 2010: Linking Undergraduate Disciplines, Washington, DC: Mathematical Association of America.

Taconis R, Ferguson Hessler MGM, Broekkamp H (2001). Teaching science problem solving: an overview of experimental work. J Res Sci Teach *38*, 442–468.

Tanner KD (2012). Promoting student metacognition. CBE Life Sci Educ *11*, 113–120.

Van Heuvelen A, Maloney D (1999). Playing physics Jeopardy. Am J Phys *67*, 252–256.

Van Heuvelen A, Zou X (2001). Multiple representations of work-energy processes. Am J Phys *69*, 184–194.

Wenglinsky H, Silverstein SC (2007). The science training teachers need. Educ Leaders *64*, 24–29.

Wilcox BR, Caballero MD, Pepper RE, Pollock SJ (2013). Upper-division student understanding of Coulomb's law: difficulties with continuous charge distributions. In: 2012 Physics Education Research Conference, AIP Conference Proceedings, vol. 1513, New York: AIP, 418–421.

Wood WB (2004). Clickers: a teaching gimmick that works. Dev Cell *7*, 796–798.