Teaching Discipline-Based Problem Solving

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ABSTRACT

Problem solving plays an essential role in all scientific disciplines, and solving problems can reveal essential concepts that underlie those disciplines. Thus, problem solving serves both as a common tool and desired outcome in many science classes. Research on teaching problem solving offers principles for instruction that are guided by learning theories. This essay describes an online, evidence-based teaching guide (https://lse.ascb.org/evidence-based-teaching-guides/problem-solving) intended to guide instructors in the use of these principles. The guide describes the theoretical underpinnings of problem-solving research and instructional choices that can place instruction before problem solving (e.g., peer-led team learning and worked examples) or problem solving before instruction (e.g., process-oriented guided inquiry learning, contrasting cases, and productive failure). Finally, the guide describes assessment choices that help instructors consider alternative outcomes for problem-solving instruction. Each of these sections consists of key points that can be gleaned from the literature as well as summaries and links to articles that inform these points. The guide also includes an instructor checklist that offers a concise summary of key points with actionable steps to direct instructors as they develop and refine their problem-solving instruction.

INTRODUCTION

Recent calls for reform in undergraduate science education such as *Vision and Change* and the Next Generation Science Standards focus on the importance of teaching core concepts and scientific practices (American Association for the Advancement of Science, 2011; NGSS, 2013). Core concepts are the principles that undergird disciplinary knowledge in the sciences, and scientific practices are the ways scientists go about using these disciplinary concepts in authentic practice. Problem solving fits nicely into these reform frameworks, because problem solving is a key scientific practice, yet it also provides a mechanism by which students obtain deep conceptual understanding. For example, imagine a student who has been asked to solve a problem about the functional differences in the spike protein mutations of SAR-CoV2 variants. In solving this problem, the student will be deepening conceptual understanding while simultaneously practicing science.

Problem solving occurs when people attempt a task for which the path to completing that task is uncertain (Martinez, 1998). Problems are the tasks themselves. Problem solving occurs in everyday life and can involve everything from deciding the route to a new location to determining the best way to approach a complex work challenge. In the academic setting, problem solving typically pertains to the challenge of solving discipline-based problems. These problems may be authentic to professional work (e.g., determining the appropriate analyses for a research data set) or related to the concepts and procedures that comprise a body of disciplinary knowledge (e.g., solving a steady-state problem in biochemistry).

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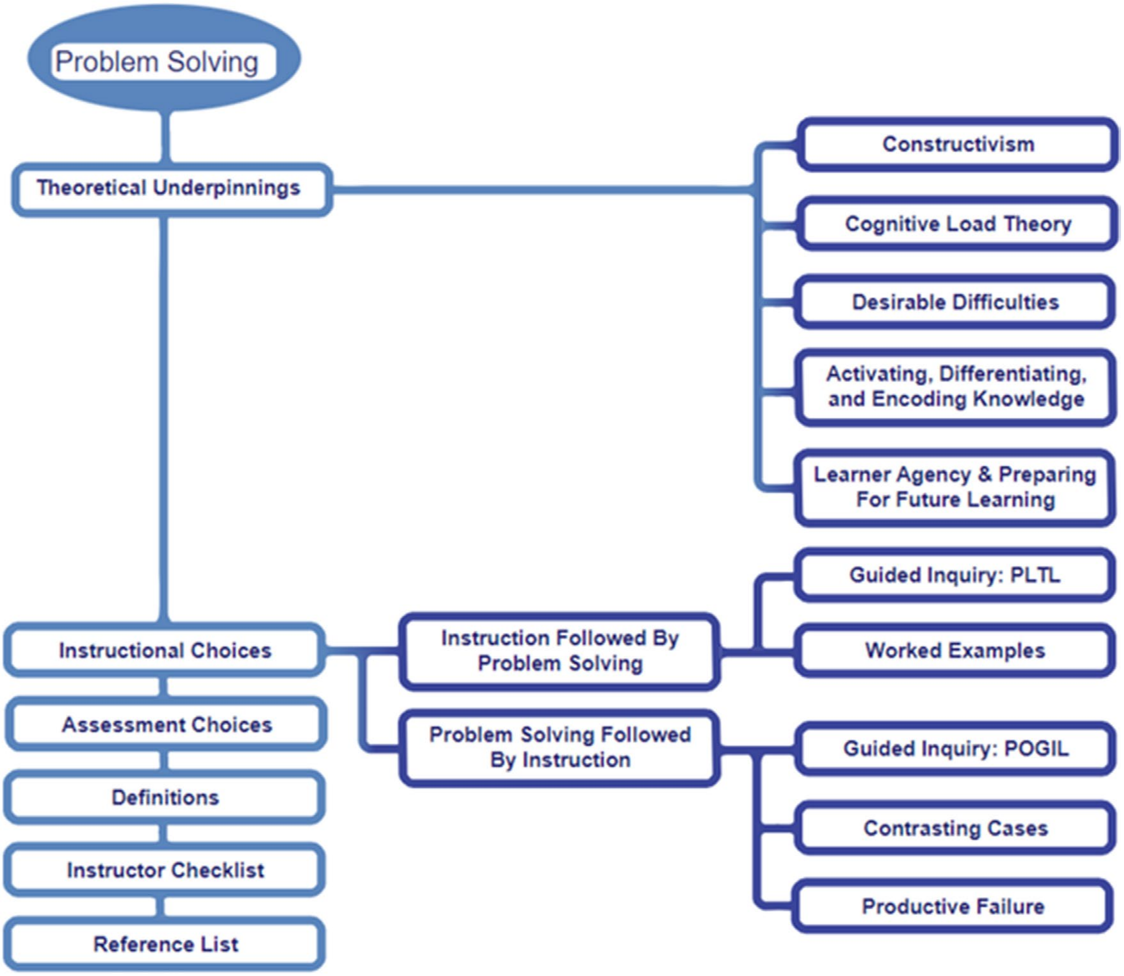

FIGURE 1. **Problem solving guide landing page**

When thinking of academic problem solving, many people automatically think of disciplines that incorporate problem types that can be solved using algorithms and heuristics. For example, mathematics, chemistry, physics, and genetics all include problems that can be solved with equations or other quantitative tools. Yet all disciplines involve problem solving, because all disciplines consist of foundational concepts that undergird the discourse and work of that discipline. For example, professional biologists conduct their research and think about their results guided by the concepts of evolution by natural selection and genetic drift, while professional biochemists rely on the concept of structure and function to guide research and development.

The aim of this evidence-based teaching guided (EBTG) is to present the evidence-base for teaching problem solving (Figure 1), and readers will benefit from considering four key advances in problem-solving research. More complete reviews of the history of problem-solving research have been provided by others (e.g., Bassok and Novick, 2012). First, the Gestalt psychologists of the 1940s investigated problem representation, that is, how people construct a model of the problem that summarizes their understanding of the problem. They found that visual aspects of problems and a solver's prior knowledge affect problem representation and, in turn, how a solver generates solutions (e.g., Duncker, 1945; Polya, 1957; Wertheimer, 1959; Bassok and Novick, 2012). Second, seminal work in the 1970s focused on the problem-solving process, theorizing problem solving as a search of the problem space for a path that connects the initial state to the solution. Researchers identified general-purpose problem-solving strategies, such as brainstorming and working backward (Polya, 1962; Simon and Newell, 1972; Jonassen, 2000). Third, work in the later 1970s and 1980s shifted away from puzzle problems to focus on knowledge-rich domains, including chess, mathematics, and physics (Chase and Simon, 1973; Hinsley *et al.*, 1978; Larkin *et al.*, 1980; Chi *et al.*, 1981; Gobert and Simon, 1996). This research confirmed the importance of prior knowledge in problem solving and crystallized the fundamental differences in knowledge organization and processing between experts and novices. Fourth, modern problem-solving research returns to the question of problem representation, incorporating new research on visual processing to clarify how problem presentation interacts with students' prior knowledge in a specific academic discipline (Novick and Catley, 2007, 2014; Goldstone *et al.*, 2010; Fisher *et al.*, 2011). Moreover, researchers have studied how to design instructional experiences in ways that support basic principles of human problem solving. They have asked the question: Given what we know about cognitive architecture and processing, how should we teach problem solving, and how can problem solving itself become an activity to facilitate learning?

This EBTG focuses on the evidence base for teaching problem solving. Our aim is to help instructors make decisions about teaching and assessing problem solving within their disciplines. We start by presenting the relevant theories that guided the development of problem-solving pedagogies, and then move to instructional choices. We focus on two key approaches that differ based on the sequence of events: instruction followed by problem solving (hereafter referred to as I→PS) and problem solving followed by instruction (hereafter referred to as PS→I). A strong evidence base exists for both approaches. We also consider the choices an instructor must make about assessing problem solving. The level of challenge of any given assessment depends on the knowledge of the person undergoing the assessment; problem-solving researchers have historically dealt with this issue using the concept of transfer. Transfer refers to the application of facts, procedures, or concepts to a new problem. Finally, we conclude by pointing out several important research questions that still need to be answered.

Note that this guide intends to synthesize our knowledge surrounding problem solving, which largely derives from the educational psychology literature. We have selected a subset of pedagogical approaches that fit within this framework and are well supported in the literature. In some cases, these approaches have been studied in undergraduate biology classes, and we have cited those papers. In other cases, the approaches have not been studied in undergraduate biology, so we drew upon research in the context of chemistry, physics, and statistics undergraduate education, as well as K–12 settings. Even though these contexts are different, we think readers can draw connections to see how they might use and test these approaches in their biology courses.

THEORETICAL UNDERPINNINGS

Constructivism is the foundation for all instructional practices that focus on active problem solving. Pedagogies for problem solving also draw on additional theories about learning, including cognitive load theory; activating, differentiating, and encoding knowledge; desirable difficulties; preparation for future learning; and learner agency.

Constructivism

A range of instructional approaches (e.g., inquiry learning, problem-based learning, case-based methods, and collaborative/cooperative methods; Prince and Felder, 2006) are all described as using a constructivist framework. Having such varied approaches can make it difficult for instructors to obtain a complete view of the constructivist theory and how it applies to these instructional approaches.

Broadly defined, constructivist theory asserts that students learn (i.e., construct mental models) by integrating new information into their prior knowledge (Bodner, 1986; Driver *et al.*, 1994). That is, students need to construct their own versions of a phenomenon based on observations or data instead of simply absorbing a version presented to them by an instructor or more advanced peers. Hence, students cannot be passive during the learning process. They must actively select information to integrate into their existing knowledge and continually test their mental model by solving problems, asking and answering questions, and discussing their ideas. Two broad categories exist in constructivist theory (reviewed by Amineh and Asl, 2015). One category aligns with Piaget's work on cognitive development. This category focuses on the individual learner's construction of knowledge to enhance or modify existing mental models. The second category aligns with Vygotsky's work emphasizing the importance of social, cultural, and historical influences on learners' knowledge construction. Vygotskian or social constructivism assumes that students' understanding of new information, their evaluation of its importance, and their sense-making of the information develop in collaboration with other learners.

Cognitive Theories and Frameworks

In addition to constructivism, other cognitive theories and conceptual frameworks underlie much of the research presented in this EBTG. One prominent theory initially described by Sweller (1988) is cognitive load theory (CLT). The basic premise concerns the level of cognitive load, or demand, that learning activities place on students' working memory. Sweller (1988) proposed that, during problem-solving activities, experts use existing mental schemas (i.e., long-term memory structures) to categorize features and move forward in the problem-solving process. Novices, however, do not have these robust existing schemas and must use cognitively demanding general strategies to try many different pathways to solve the problem. CLT explains that students learning new information must therefore rely heavily on working memory, which has limited capacity, and this high cognitive demand can impede learning underlying problem features. I→PS approaches address this issue by introducing students to new concepts before asking them to actively apply the concepts during problem solving. Providing instruction first arguably helps students transfer the information to long-term memory, which is not capacity limited like working memory, and results in a low cognitive load. When students subsequently solve problems, they can retrieve the information from long-term memory and dedicate their working memory resources to detecting underlying problem features. Extensive research supports CLT and the effect of limited working memory capacity on student learning (Sweller *et al.*, 2019).

Several other cognitive theories and conceptual frameworks can serve as alternative lenses to understand instruction that uses and fosters problem solving. For instance, rather than focusing on the limitations of working memory, instructors might consider how to help students activate, differentiate, and encode knowledge. As noted earlier, learning requires integrating new information into prior knowledge (e.g., models for phenomena) and addressing any conflicts between the two. PS→I approaches can facilitate this process by prompting students to activate their current mental models, find similarities and differences with their prior experiences and the new information presented, and incorporate variation and critical features of the novel problem into refined mental models. In other words, having students explore new problems first, without prior instruction on the underlying principles, can prompt students to engage in abstract processing rather than simply seeking the solution, resulting in better conceptual learning and transfer to new contexts (DeCaro and Rittle-Johnson, 2012). PS→I can be especially beneficial when it invites students to compare cases and invent general principles to explain the observed variation (Schwartz *et al.*, 2011).

This approach also aligns with the preparation for future learning theory, which emphasizes students' readiness to interpret and generate understanding from novel resources and activities. Research shows that the exploration and invention before direct instruction that occurs in PS→I approaches can ultimately help students extract more information from novel *future* materials, preparing them to independently develop and transfer conceptual understanding (Schwartz and Martin, 2004; Belenky and Nokes-Malach, 2012).

The concept of desirable difficulties can also be used to understand instruction that promotes the development of problem-solving ability. While students may prefer strategies that provide quick familiarity and an easy sense of understanding (e.g., rereading), the introduction of cognitive challenges into the learning process can generate better long-term learning outcomes (Schmidt and Bjork, 1992). Such desirable difficulties include requiring students to retrieve information from memory to solve a problem (i.e., retrieval practice) and spacing out practice across varying intervals of time (i.e., distributed practice; Dunlosky *et al.*, 2013). In general, activities where students must actively generate and even struggle to find solutions, instead of following a prescribed and known procedure, will encourage deeper processing of the information. Thus, while PS→I approaches (e.g., invention tasks) might introduce difficulties – slower and effortful learning, more errors, and apparent forgetting of information–they offer the long-term benefits of improved retention and transfer.

Affective Dimensions

While most studies presented in this EBTG focus on the cognitive processes underlying problem-solving pedagogies, recent research has begun to consider student perceptions and affect as well. When complex problem solving is designed to engage students in desirable difficulties, the experience of struggle may undermine student motivation and confidence. As a result, problems should be calibrated to student characteristics (e.g., prior knowledge), so they are achievable with support and structure. Instructors must try to cultivate students' motivation and confidence, so students can cope with or even embrace the difficulties they encounter (Zepeda *et al.*, 2020).

One approach to improving motivation is to foster *learner agency*, or a sense of ownership, by providing choices during the problem-solving process (Zepeda *et al.*, 2020). Students who have agency in their learning are more motivated and engaged, with positive effects on learning outcomes. PS→I approaches encourage students to test out different ways to solve a problem (DeCaro and Rittle-Johnson, 2012), especially when the students are discussing ideas in small groups. Even when this generative process results in incorrect responses, it can instill learner agency and prepare students for self-directed learning in the future (Schwartz and Martin, 2004).

Another motivational benefit of PS→I approaches is the way they direct students' attention toward growing their understanding (i.e., a learning or mastery goal) rather than simply finding the correct solution (i.e., a performance goal). Students with mastery orientations show better transfer of problem-solving skills, and invention activities before explicit instruction can lead students to adopt such mastery goals, at least in the short term (Belenky and Nokes-Malach, 2012). Such activities immerse students in the process of discovering underlying features and principles, rather than applying a prescribed procedure to solve the problem.

INSTRUCTIONAL CHOICES

The theories and frameworks that can help us understand instruction that fosters problem-solving abilities leave an array of instructional choices. Our guide organizes the literature on choices about the sequencing of instructional activities into I→PS and PS→I. The I→PS section focuses on peer-led team learning and worked examples plus practice. The PS→I section focuses on process-oriented guided inquiry learning, contrasting cases, and productive failure. Other pedagogies exist that could be included in these sections, but we have selected the ones for which a strong evidence base exists and guidelines for implementation are well delineated. Readers should note that not all these pedagogies originated with an eye toward the I→PS versus PS→I distinction. However, contemporary research points out that the literature on problem-solving instruction can be reorganized based on this distinction. Doing so reveals a testable research question that cuts across pedagogies and is not yet fully answered (Kapur, 2016; Loibl *et al.*, 2017): What are the benefits and limitations of instructing first and then asking students to solve problems versus giving them problems to solve and then following with instruction?

Sequencing Instructional Activities: Instruction Followed by Problem Solving

In I→PS, instructors provide explicit instruction to students before asking them to solve problems. The explicit instruction teaches students the procedure for solving a problem or the concepts involved in solving the problem. Two common I→PS approaches include peer-led team learning, which is a form of guided inquiry, and worked examples plus practice.

Peer-Led Team Learning. Peer-led team learning (PLTL), which originated in undergraduate chemistry education (Varma-Nelson *et al.*, 2004); (Wilson and Varma-Nelson, 2016) and is popular in undergraduate biology education as well (e.g., (Preszler, 2009; Snyder *et al.*, 2016), involves students working in collaborative groups to solve prepared problems facilitated by a trained peer leader. PLTL is an I→PS approach, because students first receive explicit instruction about concepts and procedures in a traditional lecture and then attend PLTL sessions to collaboratively practice applying the concepts and procedures to a problem set. Course instructors write the weekly problem sets and design them to be collaborative exercises that engage students in reasoning and increase in complexity from start to finish. Peer leaders guide students to solve the problems with their group members (Repice *et al.*, 2016). PLTL works best when the PLTL sessions are an integral part of the course and course instructors organize the program and train peer leaders (Varma-Nelson *et al.*, 2004).

PLTL derives from the theory of social constructivism. Students must develop their conceptual understanding and problem-solving ability through active engagement with the material and sense-making done in collaboration with other students. PLTL sessions provide a social constructivist environment, in that students participate in problem solving and conceptual development with their peers, guided by a more knowledgeable peer (Wilson and Varma-Nelson, 2016).

This guide helps readers understand the characteristics and evidence base for PLTL by focusing on articles about key components (e.g., Wilson and Varma-Nelson, 2016) and outcomes, including improvements in exam performance and reductions in drop/fail/withdrawal rates that are particularly profound for students from underserved groups (e.g., Frey *et al.*, 2018). Finally, the guide summarizes studies that describe the types of discourse among PLTL groups, showing that groups engage in talking science, sense-making, and authentic scientific practice (e.g., Bierema *et al.*, 2017).

Worked Examples plus Practice. Worked examples plus practice originated among educational psychologists who attempted to develop an instructional strategy that aligns with CLT (e.g., (Tuovinen and Sweller, 1999). Researchers aimed to create a pedagogy that would enhance support for intrinsic cognitive load, that is, the cognitive load that comes from the inherent challenge of the procedures and concepts to be learned. For example, it is inherently demanding to conceptualize the electrostatic charge around an atom. At the same time, researchers aimed to reduce extraneous cognitive load, that is, the cognitive load that comes from the way procedures and concepts are taught. For example, it is unnecessarily demanding to conceptualize the electrostatic charge around an atom without a model or visual representation. Researchers achieved this feat through the worked examples plus practice pedagogy, which has been tested in a range of disciplines and educational levels (Atkinson *et al.*, 2000; Kalyuga *et al.*, 2001; Nievelstein *et al.*, 2013; Halmo *et al.*, 2020).

Worked examples plus practice involves leading students through a problem solution in a step-by-step manner followed by a practice problem. Worked examples plus practice is an I→PS approach, in that the worked examples, sometimes accompanied by additional elaboration by the instructor, provide explicit instruction in the procedures and concepts to be used for solving the problem. Then students take time to solve practice problems, presumably applying the procedures and concepts they have seen in the example. Ideally, this approach involves multiple rounds of worked examples followed by practice problems.

Worked examples plus practice can be an effective instructional approach in helping students to solve problems like those used during instruction (i.e., near transfer; see *Assessment Choices*). This benefit appears to be limited to novices within a domain (Kalyuga *et al.*, 2001). Critics of this approach suggest that it may hamper students' deep conceptual understanding and far-transfer problem solving, arguing that reducing cognitive load short-circuits desirable difficulties that help students recognize and encode the deep principles underlying a challenging problem (Kapur, 2016).

This guide helps readers understand the characteristics of and evidence for worked examples plus practice. Summaries and links to papers from the late 1990s and early 2000s show readers how the approach took shape based on CLT, while more current references provide details about how to implement this approach and present evidence for its efficacy.

Sequencing Instructional Activities: Problem Solving Followed by Instruction

In PS→I, students solve problems before receiving explicit instruction on relevant procedures and concepts. Three common PS→I approaches include process-oriented guided inquiry learning, contrasting cases, and productive failure, and we expand on these approaches in this section. Readers may also be interested in learning more about problem-based learning (Allen and Tanner, 2003; Anderson *et al.*, 2005; Anderson *et al.*, 2008).

Process-Oriented Guided Inquiry Learning. Process-oriented guided inquiry learning (POGIL) presents students with conceptual models of the material to be learned and a series of questions that walk students through the process of understanding, explaining, and solving problems pertaining to the model (Moog, 2014; Loertscher and Minderhout, 2019; Rodriguez *et al.*, 2020). Students work in collaborative groups of three to four students during class time. POGIL instructional materials provide structured guidance prompting students to explore, understand, and apply a conceptual model. The materials also guide students to develop skills in communication, teamwork, management, and critical thinking. Class sessions contain little or no traditional lecture. Rather, explicit instruction is provided as the instructor facilitates collaborative groups and directs and responds to structured, intermittent report-outs by groups to the entire class (Moog, 2014; Rodriguez *et al.,* 2020). We present POGIL as a PS→I approach, because problem solving always occurs before explicit instruction, even though the phases of problem solving and instruction are more intermingled than with productive failure and contrasting cases.

POGIL derives from the theory of social constructivism (reviewed by Amineh and Asl, 2015), like PLTL. POGIL provides a social constructivist learning environment where students participate with one another in problem solving facilitated by their instructor, the more knowledgeable guide. Collaboration and guidance offer continuous sense-making opportunities whereby students refine their knowledge and build their skills.

The guide summarizes papers that detail how POGIL is implemented and the impacts of POGIL on student learning and achievement, particularly when compared with traditional lecture (e.g., Vincent-Ruz *et al.*, 2020). The guide also summarizes research on the impact of POGIL on student reasoning and discourse (e.g., Moon *et al.*, 2016).

Contrasting Cases. Contrasting cases are problems that differ in key features. Comparing the cases can help students identify deep features of the problem type and facilitate conceptual understanding (Schwartz *et al.*, 2011). Contrasting cases have been used in a variety of ways, including before and after direct instruction (Roelle and Berthold, 2015), to prompt students to invent the principle that unites the cases (Shemwell *et al.*, 2015), and to prompt students to understand experts' descriptions of the similarities and differences in the cases (Newman and DeCaro, 2019). We present contrasting cases as a PS→I approach, because they are generally found to be more beneficial when used before explicit instruction (Alfieri *et al.*, 2013). The guide summarizes papers that show the efficacy of contrasting cases for student learning compared with other approaches, including lecture followed by practice problem solving. The guide also summarizes various uses of contrasting cases and the outcomes of these different uses.

Productive Failure. The productive failure hypothesis suggests that, under certain conditions, solving ill-structured problems that are beyond students' skill sets and abilities can promote learning, even though failure may initially occur (Kapur, 2008). Thus, in the productive failure approach, students initially attempt complex problems that are beyond their capabilities. Instructors then provide explicit instruction that reveals conceptual knowledge and problem-solving procedures. The guide summarizes seminal papers that explain the rationale and supporting literature for the productive failure approach, as well as studies that document improved learning outcomes for this approach (e.g., Kapur, 2011).

Both contrasting cases and productive failure ask students to solve complex, challenging problems. While these approaches to instruction originated and have been investigated independently, a recent review examined the evidence for these two approaches and lumped them under the broader umbrella of PS→I approaches (Loibl *et al.*, 2017). This review emphasized that both approaches can be effective in promoting conceptual understanding and problem solving if they include one of two features: 1) The initial challenging problem includes contrasting cases, that is, problems that differ in key features and thus draw students' attention to the nuances of the underlying principles. (2) The explicit instruction phase builds on student work generated during the problem-solving phase. Instructors do this by drawing attention to the ways students attempted to solve the problem and connect those attempts with canonical solutions to the problem (Loibl *et al.*, 2017).

Additionally, both productive failure and contrasting cases arise from similar theoretical orientations (Kapur, 2008; Schwartz *et al.*, 2011). First, both draw on the notion that learning requires the activation and differentiation of prior knowledge. Learners develop conceptual understanding as they sort out their relevant knowledge and discover gaps and limitations in their prior knowledge. Solving a complex, challenging problem may cause students to activate a wide range of prior knowledge, identify things they need to know but do not know, and begin to differentiate more and less important knowledge. Second, both draw on preparation for future learning, the idea that the main benefit of a learning experience may be that it sets up a student for greater learning in the future (Schwartz and Martin, 2004; Belenky and Nokes-Malach, 2012). An initial, challenging problem-solving phase will have fewer short-term gains than explicit instruction, but the effort and cognitive activation and differentiation likely prepare the learner to benefit greatly from subsequent explicit instruction. Third, both draw on the concept of desirable difficulties (Schmidt and Bjork, 1992). Learning requires effort, and effort that is appropriate and well managed can benefit learning in the long run, even though it is more difficult in the short run. Fourth, both focus on the importance of learner agency (Zepeda *et al.*, 2020), pointing out that challenging students initially and then supporting them more explicitly can build learners' confidence and support them to take greater responsibility for their learning by teaching them to determine for themselves what they do and do not need to learn.

ASSESSMENT CHOICES

Evidence-based instructional practice involves backward design (Wiggins and McTighe, 1998). Instructors first define the learning objectives and next decide how they will measure students' accomplishment of the objectives. Instructors whose objective is for students to learn problem solving must also assess problem solving. What is a problem-solving assessment? A problem-solving assessment is simply a problem. It requires students to complete a task for which the solution is unknown in advance (Martinez, 1998). Yet even a problem for which the solution is unknown in advance may be more or less challenging for a student based on the similarity of the problem to instruction. Historically, researchers have dealt with this issue through the concept of transfer.

Transfer describes students' ability to solve problems that extend beyond the examples that are directly taught. It deals with students' ability to use knowledge in a new context. The guide introduces readers to a taxonomy of transfer (Barnett and Ceci, 2002). While most science instructors think first about cognitive transfer (e.g., concepts and procedures), the Barnett and Ceci taxonomy provokes broader thinking, proposing nine dimensions along which transfer can be considered, such as knowledge (i.e., the content of a particular field to which the task is to be applied), functional context (e.g., Is the task positioned as an academic activity or a "real-world" activity?), and social context (i.e., Is the task learned and performed individually or in a group?).

Regardless of the dimension of transfer, instructors must consider how near versus far the transfer problem will require students to go from the original learning environment. A problem that is similar to an example encountered in class or homework can be thought of as a near-transfer problem. Because there is a large overlap between the original learning situation and the new problem, solving the new problem requires students to do something like the previous exposure. On the other end of the spectrum, a far-transfer problem involves concepts to which the learner has previously been exposed but cannot solve with a previously used method. Rather, the learner needs to comprehend the underlying concepts and generate solutions, either by applying the concepts in a different manner or integrating across multiple concepts. Far-transfer problems bear little similarity to the original learning situation. McDaniel and colleagues (2018) and Frey and colleagues (2020) developed a rubric with specific example problems to show and characterize near- and far-transfer problems in general chemistry.

The guide also considers the issue of problem representation as it pertains to assessment. Recall that problem representation refers to the mental model a solver constructs that summarizes understanding of the problem (Bassok and Novick, 2012). When students learn via problem solving, they form problem representations. Exemplar learners rely extensively on memorization of specific example problems or algorithms to represent the problems they learned, while abstraction learners develop representations that pertain to the underlying concepts of the problems they learned. These different learning approaches result in similar performances on near-transfer problems, but abstraction learners achieve higher performance on far-transfer problems (McDaniel *et al.*, 2018).

In addition to knowledge transfer being affected by instructional choice, other outcomes (such as affective outcomes) may be influenced, and hence instructors may want to assess these outcomes. For example, invention or problem solving first approaches have been shown to improve motivation (Belenky and Nokes-Malach, 2012) and increase engagement and improve students' ability to develop multiple solutions (Taylor *et al.*, 2010). Often self-report surveys, process-oriented rubrics, and observation data are used to assess these outcomes.

Thus, the guide provides information that should help instructors as they develop an assessment plan, determining 1) what outcomes should be assessed by looking at course objectives and examining the range of transfer dimensions available; 2) what degrees of transfer are of interest and how to develop the questions based on these degrees; and 3) whether there are surveys, rubrics, or other types of data that could be used to assess affective or behavioral outcomes.

EMERGING ISSUES IN PROBLEM-SOLVING RESEARCH AND IMPLICATIONS FOR INSTRUCTION

The guide points to the strong evidence base for I→PS and PS→I approaches to problem-solving instruction and helps instructors delineate the different ways to assess students' problem-solving capacity. Overall, these data show that both I→PS and PS→I approaches produce superior learning gains compared with traditional approaches like lecture alone. Yet important research questions remain (Lobato, 2012; Kapur, 2016; Toh and Kapur, 2017; Ashman *et al.*, 2020; Chen and Kalyuga, 2020). These questions include:

- What is the impact of problem-solving pedagogies across different subdisciplines of biology and different topics in biology?
- What is the role of guidance during problem-solving instruction? Do students benefit from explicit structures that fade away as they learn, or are there important benefits to leaving students to solve problems without assistance?
- What is the role of prior knowledge? Do different instructional approaches work better for students with more limited prior knowledge, while others work better for students with more prior knowledge?
- Are there specific problem types or student characteristics that make problem-solving sequencing before or after instruction better or worse?
- How can instructors structure their lessons to provide opportunities for transfer? What does it look like for students to practice transfer?
- Arguably, problem-solving research should not be limited to measures of transfer that are purely defined by experts. How can we use other methods, such as classroom observations, focus groups, and interviews, to capture the application of learning (i.e., transfer) from the perspective of the student as opposed to the expert?
- Problem-solving research historically has focused on cognitive outcomes, yet the affective impacts of instruction certainly make a difference to student learning and development. Do different approaches to teaching and assessing problem solving result in differential impacts on student interest, motivation, self-efficacy, and sense of belonging?

Despite these outstanding questions, instructors who take the time to consider the gathered evidence for problem-solving instruction and assessment, connect the evidence to learning theory, and critically engage with the outstanding questions will be well equipped to examine their own teaching and improve their capacity for teaching problem solving. In addition, these considerations can prompt the development of experiments in and outside the classroom to better understand the affordances and limitations of different approaches to teaching problem solving.

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