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Improved Teaching of Science and Engineering Using Deliberate Practice of Problem-Solving Decisions

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Abstract

The ability to solve complex realistic problems is the most important requirement for being a good scientist or engineer. Here we present a theoretical design for improving the effectiveness and efficiency in teaching technical problem solving at the post-secondary level. The approach brings together theoretical ideas and empirical results from (a) evidence-based instructional practices, (b) development of expertise through deliberate practice, and (c) a decision-based framework for complex problem solving. This design involves explicit practice and feedback on making the set of decisions that define the problem-solving process of skilled scientists and engineers. We provide a template for instruction based on this design. This design also provides a way to assess problem-solving skills that is more accurate than traditional examinations.

Keywords: problem-solving decisions, STEM teaching, deliberate practice

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Introduction and Background

The most important skill that science and engineering ("S & E") students need to learn from post-secondary education is how to solve "real-world" problems. The value of skilled scientists and engineers in the modern world is their ability to solve novel complex problems with no obvious solution and involving many different factors, not all of which are known. Examples of such problems are developing and applying the science and technology needed to adapt to climate change; reducing the impact of prevalent and future diseases; or developing a cheap, flexible, low power mobile phone display. The problems ("school problems") that dominate S & E instruction, however, only teach students to solve familiar problems that can be solved by following standard procedures when all the necessary information is given. Despite the importance of mastering complex real-world problem solving, there are no proven methods for teaching and measuring such problem-solving skills, and there are many demonstrations that traditional instruction with traditional school problems is ineffective at teaching these skills. In this paper, we propose a theoretical approach to teach these essential problem-solving skills in S & E courses by combining advances from (a) evidence-based S & E instructional practices, (b) acquisition of expertise through deliberate practice, and (c) characterization of technical problem solving in terms of specific decisions.

Evidence-Based Instructional Practices

In recent decades there has been extensive research comparing the effectiveness of different forms of instruction in higher education. The most extensive and compelling results have come from "discipline-based education research," which studies the learning of specific topics in science and engineering (Singer et al., 2012). Particular instructional approaches, often called "active learning" have been shown to be highly effective, much more effective than traditional didactic lecture, for teaching concepts in introductory physics and other science subjects (for a review of this extensive field, see Singer et al., 2012). These forms of instruction vary in the details but generally involve students spending class time answering questions that require application of the basic concepts to be learned. The students discuss their answers and get feedback on them from both their peers and the instructor. This approach has shown enhanced performance of students on "concept tests" that probe the relevant conceptual mastery

(Freeman et al., 2014; Hake, 1998). However, in most implementations there is little practice of the other cognitive processes required for solving complex problems, and so less change is observed in performance on typical physics calculational problems (Crouch & Mazur, 2001; Freeman et al., 2014; Thacker et al., 1994).

Acquisition of Expertise Through Deliberate Practice

An important advance in this field was the work of cognitive psychologist A. Ericsson on the nature of expertise and how it is developed. He developed an empirically based theory of the development of expert skills which he labeled "deliberate practice" (Ericsson, 2006). He and others have shown that this process is used in most, arguably all, fields in which high levels of measurable skill are demonstrated. We argue that it will apply to S & E problem solving. Deliberate practice has three primary elements.

- Identifying all the subcomponents of the expertise. In music or sports the subcomponents include both physical and cognitive elements, such as holding the violin bow properly and recognizing the proper note; while in intellectual activities, like chess or science, the subcomponents are almost entirely cognitive.
- Intently practicing each subcomponent for large amounts of time.
- Accompanying this intense practice with reflection based on feedback, often from a teacher or coach, on how to improve, and then incorporating this feedback into further practice.

The concept of deliberate practice is consistent with brain studies in humans and animals that show that extended intense thinking on a task modifies the neuronal connections to enhance the brain's ability to carry out the relevant mental task. In this regard, the mental development of expertise is closely analogous to the development of a muscle. With, and only with, intense exertion of that muscle for an extended period will it become larger and stronger, better able to complete the tasks it is being called upon to carry out. Low level or casual practice shows little benefit on improvement of performance (Ericsson, 2006), just as using a muscle very lightly results in little change in strength. Our theory is based on this analogy. The brain needs to be provided with specific mental exercise to develop the specific cognitive capabilities needed for S & E technical problem solving. One important aspect in which this analogy fails is that the body can strenuously exercise many muscles at the same time, but it cannot focus on many different cognitive activities at the same time. The limited capacity of the short-term working memory limits how many things the brain can pay attention to at once (Baddeley, 2007). This is likely the reason that, as described by deliberate practice, expertise is best gained by decomposing the skill into small sub-components and practicing to master those sub-components individually. Each sub-component has a small enough set of cognitive demands that working memory is not overloaded, so each of those demands can receive full attention.

While there have been extensive studies showing the value of deliberate practice in developing expertise across a variety of areas (Ericsson et al., 2018), there has been a fundamental problem with applying deliberate practice to teaching S & E problem solving. Such problem solving is a complex activity, involving many cognitive actions and applying a variety of knowledge, but the full set of cognitive skills required for complex problem solving had not been identified. Lacking that identification, all a teacher could do was to have the learner practice "solving complex problems." That is such a broad task encompassing so many different cognitive tasks that the learning process is not deliberate practice and is hence less efficient. It is analogous to teaching a person how to play golf by only telling them that what matters is how many strokes it takes put the ball in the hole, and they should keep practicing until they require few strokes. What a good coach provides instead is feedback on, and individual practice of, all the specific skills required for playing golf: holding the club properly, how to hit putts, how to judge distance from the hole, how to hit drives, etc. This is deliberate practice at learning to play golf.

Characterization of Technical Problem Solving

While there has been much previously written on technical problem solving (for reviews see Csapó & Funke, 2017; Singer et al., 2012), it has not been characterized sufficiently to allow teaching in a way that would be equivalent to what a good athletic coach provides. Research on teaching S & E problem solving has almost entirely focused on solving school problems, rather than improving the skills needed for the complex problems encountered by practicing scientists or engineers (Dörner & Funke, 2017; Heckler, 2010; Heller & Hollabaugh, 1992; Kuo et al., 2017). Other studies have primarily looked at only narrow slices of the process, for example, probing how experts and novices in a subject organized their knowledge differently (e.g., Chi et al., 1981; Larkin et al., 1980; McCloskey, 1983). There is also extensive advice on problem solving based on anecdotal reports and individual reflections, but with little empirical evidence as to their completeness or accuracy (Heller & Reif, 1984; Polya, 1945). Other work has focused on "domain general" problem-solving practices, but those neglect the essential role that disciplinary knowledge plays in the process of solving authentic problems (see Frensch & Funke, 1995; Funke & Frensch, 2007 for reviews). An exception is the "naturalistic decision making" area of research. This work takes a more empirical approach to investigate problem solving and expertise in real-life work settings and has been used to identify critical decision points (Mosier et al., 2018), though the focus is usually on the domain-specific details of how those decisions are made rather than the general problem-solving process.

The research of Price et al. (2021) drew upon the naturalistic decision-making approach to investigate the problem-solving process of many S & E experts, focusing on what decisions need to be made. These were generalizable beyond the specific problem being solved. Price et al. framed the S & E problem-solving process as a set of 29 decisions that they found S & E experts consistently made during the solving process. These were decisions like, *What information is needed to solve this problem? What approximations and simplifications are appropriate? How can I get this information? Which calculations and data analysis are needed? How credible is the information [obtained], and what conclusions can I draw from it?* The experts were found to use their disciplinary knowledge and experience to make choices for all the decisions. Their knowledge was organized in the form of discipline specific mental models that were optimized for making such choices wisely (Price et al., 2021). This use of mental models is consistent with previous studies of how expert knowledge is organized to allow efficient identification of important underlying features when solving problems (Charness, 2008; Egan & Greeno, 1974; Klein, 2008; Larkin et al., 1980). Recognizing which knowledge is relevant to a particular problem and how to apply it are important expert judgements.

Approach to Instruction Based on Deliberate Practice of Problem-Solving Decisions

Our theory of instruction is that to learn real-world S & E problem solving, students must deliberately practice making these specific problem-solving decisions in the context of realistic problem scenarios. This implicitly assumes a constructivist theory of learning (Piaget, 1971). Deliberate practice exercises their brains in the necessary way to develop S & E problem-solving expertise. The problem-solving decisions define the set of cognitive skills a student needs to practice and master to develop expertise in a subject. Expertise means coming to a decision (choosing an action or conclusion) similar to that of a skilled practitioner in the discipline, along with a similar justification for the choice. Our theory goes beyond most discussions of deliberate practice for expertise in one small way: the relevant linkages between the sub-components and how those are practiced. Price et al. (2021) saw that many of the decisions were coupled, so the problem-solving process not only required making individual decisions, but also recognizing and acting on how the results of one decision modified past or future decisions. This implies that the necessary practice does not only involve mastery of the sub-components, but also, as those are developed, practicing them in the context of combining them to solve the larger problem. While this combining stage in the learning process is seldom explicitly mentioned in the studies of expertise acquisition in the work of Ericsson and others, it is often implied. We mention it here, because of its relevance to formal instruction.

This provides a general theory for the learning of S & E problem-solving skills. The next step is the development of instructional tasks and feedback to provide students with deliberate practice in the problem-solving decisions, including acquiring the knowledge and knowledge organizational structures needed to make those decisions.

We propose a way to implement this theory in the context of teaching post-secondary/university S & E courses using a modified version of "backwards design" (Wiggins & McTighe, 2005). Traditional backwards design involves (a) establishing learning goals (sometimes called "objectives"), (b) deciding what evidence or assessment measures will determine how well students achieve those goals, and (c) creating instructional materials and activities to achieve those goals. Consistent with (a), we identify the learning goals as "have students learn to solve complex problems by making good problem-solving decisions in the context of the respective discipline." However, assessment and instruction cannot be divided into sequential steps as suggested by Wiggins, because targeted timely feedback, which requires assessment, is a necessary ongoing component of deliberate practice activities. So, assessment and feedback ("formative assessment") must be built into the instructional activities as an integral part to their design. In Decision-Based Instruction Worksheet Template, we present a template for designing problem worksheets that provide students with practice and feedback on problem solving decisions in any S & E discipline. This template can be applied to many different subjects and grade levels and can serve equally well for instruction and assessment.

In an instructional activity designed to practice problem-solving decisions, learners would work through a problem, making and justifying the various decisions by answering the same kinds of questions that experts would need to answer, tailored to the appropriate level of required content knowledge. The types of problems a student could be expected to solve would depend on their level of knowledge. As they make decisions, they need to receive timely, specific, and actionable feedback on how to improve their decisions (Schwartz, 2016). Timely means it needs to be after they have completed the thought, but soon enough that they can still remember their thinking. Specific means it needs to address the positive features but more importantly, the negative features of the thinking. Actionable means it needs to provide guidance on how they can improve that thinking. Such feedback can be provided by student peers and the instructors if both are sufficiently informed as to how the learner is thinking. The widespread "active learning" classroom approach of small-group work with instructor monitoring and guidance provides an opportunity for such practice with the necessary timely, specific, and actionable feedback.

Table 1

A Set of Best Practices for Implementation

Use “problem-based” instruction in which students first engage with a meaningful problem and then learn the relevant knowledge in the process of solving
Problems and questions are appropriately challenging but attainable for the student population
Explicitly require making and justifying decisions
Provide multiple contrasting cases to enhance the recognition of underlying principles and how to apply them to solve new problems
Require applying the knowledge to be learned to solve the problems
Relevant and meaningful context to motivate learning
Problem-solving worksheets to be completed in class with clear deliverables (individual and group)
Have suitable forms of pre-class preparation activities (Wieman, 2016)
Students work together in groups of 3-4 on answering worksheet questions, monitored by instructional team; optimum use of small group activities
Feedback is timely, specific, and actionable
Establish norms for group behavior and collaboration
Get student buy-in to the instructional approach by discussing its rationale and benefits
At appropriate intervals, instructor provides feedback and guidance to the whole class

This instruction would be implemented similarly to the manner described by Jones et al. (2015) and Lepage (2021) (Figure 1), which follows established best practices for instruction (Table 1). Each student would have a worksheet (paper or computer-based) to complete during class and then submit to the instructor for grading/feedback. The worksheet would have the problem scenario and the various decision-based questions listed on it (Figure 2). The students would work in groups of three or four, each student first writing out the decision and justification in their own words but then discussing the ideas and answers with their group and revising their previous responses as needed. While they do this, the instructor, and teaching assistants if available, would monitor their discussions and answer questions from individual groups as needed. At appropriate times, the instructor would pull the class together to provide feedback, answer questions, and ensure everyone had reached an appropriate level of understanding. Often, the instructor would poll all the students in the class on the answer to a multiple-choice question based on a worksheet question. This provides the instructor with additional information as to how well all the students mastered the relevant ideas, and it can focus student attention on some particularly important or challenging idea. After the whole class feedback session, the students would return to working in their groups to complete the worksheet. Working in groups provides multiple benefits: it gives the students ongoing feedback through discussions with their peers; it provides the benefits of social learning (Schwartz, 2016); and it allows them to solve more challenging and interesting problems than many students could complete on their own in a reasonable amount of time.

Figure 1

Implementation Approach

Iterate Through Problem

Time	Materials	Student Action	Instructor Action
A few minutes		Listen	Introduce task and context
Several minutes	Decisions-based Problem Worksheet (See Fig. 2)	Write individual choices and justifications	Circulate, monitor, provide guidance as needed
5-20 minutes		Discuss in groups of 3-4, revise choices as needed	
5-10 minutes		Listen, ask questions, respond to poll questions	Lead whole-class discussion & polls, provide feedback & explanations

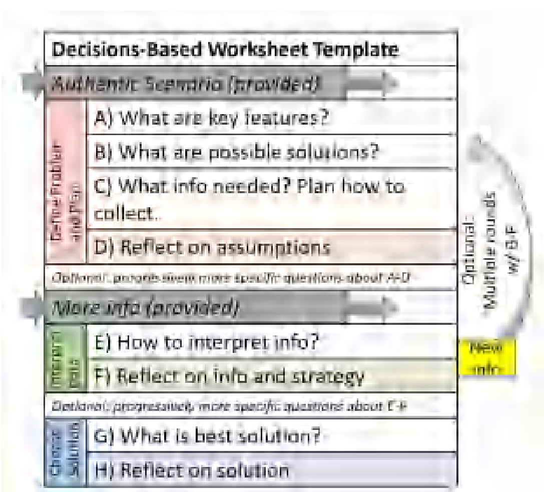
This implementation approach provides a general structure for the sequence of activities to provide the desired deliberate practice in problem solving. A critical component to this is the design of the worksheet that students complete. That determines the specific thinking they will be doing. The next section provides a template for translating our theory into a worksheet task for students. Although we present this in the context of what might be done in a classroom, much of it could also be adopted to homework problems.

Decision-Based Instruction Worksheet Template

Figure 2 shows a design template for a worksheet that provides students with practice and feedback at making specific problem-solving decisions. The specific questions and information provided in the worksheet can also add support for students. Supports could include rescue points where important features are specified or information is given, in case the students did not decide to consider those on their own, or reasonable but flawed solutions or data-collection plans for the students to critique and improve upon.

Figure 2

Template for Designing Decisions-Based Instruction Worksheets (Adapted From Price et al., 2022)



The worksheet starts with a realistic problem scenario that contains realistic irrelevant and incomplete information and has multiple possible solution paths. To solve should require knowledge that learners are expected to know or learn during the process. The worksheet then calls upon learners to make decisions, while providing their reasoning and explaining information used to arrive at and justify their choice.

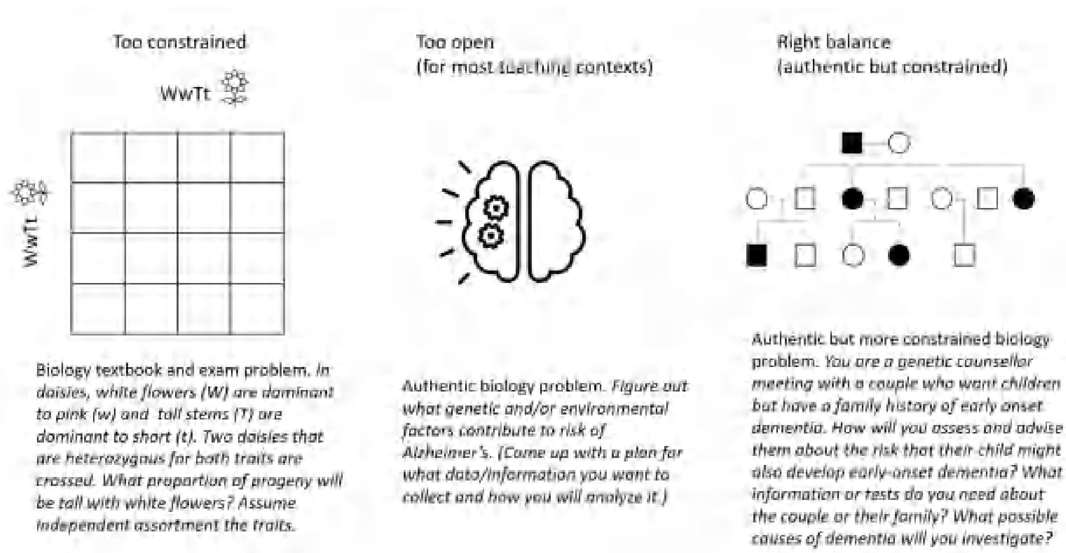
A critical instructional decision is selecting a problem with the appropriate balance between authenticity and instructional practicality, including what knowledge and decisions are needed to solve the problem. The problem scenario and decision-prompting questions should constrain the solver but not too much. See Figure 3 for some example scenarios. Too much constraint means the important resources and decision processes of the expert are not practiced. Most textbook problems fall in this category—they have many important decisions removed in the problem statement, so students do not need to decide what information is needed, how to find that information, what assumptions are appropriate, etc.

Figure 3

Examples of Overly Constrained, Under Constrained, and Optimally Constrained Problems

A

B



Note. Panel A: Physics (from Wieman, 2022). Panel B: Genetics (biology).

The problem scenario should be followed with a series of questions that ask the students to make different decisions. In Figure 1, we include particularly important decisions to probe. An important part of problem solving is recognizing what information is needed and correctly applying relevant information. Thus, the decisions involved in this are practiced by asking students to decide what information is needed, providing new information, and then asking them to interpret and reflect. These decisions often require the solver to make additional decisions, which the instructor can explicitly probe as appropriate for the problem. The specific sequence of questions should follow the approximate order an experienced solver would use for that problem.

The questions need to be sufficiently constrained to make the student responses be interpretable, but not so constrained that the decisions are removed. For some problem scenarios, the range of possible student responses is excessively large. A technique that is useful in that case is to offer a flawed solution, plan, or design, and ask the student to evaluate the proposed solution, a form of troubleshooting. This troubleshooting still provides the student with most of the desired cognitive practice, because the expert problem-solving process involves formulating a set of potential solutions and evaluating how well they meet necessary criteria, but it adds a form of scaffolding to constrain the question to be in an educationally more effective structure.

Most of the template questions serve as scaffolding to help learn the problem-solving process. They tell the students what decisions they need to make, but not what choice they should make for the decision. Then feedback is provided on the choices made. Such “scaffolded agency” has been shown to provide large educational benefits (Holmes et al., 2020). To provide optimum deliberate practice in problem solving, the scaffolding should be reduced as the students gain more practice, so eventually they are able to work through making all the decisions they need to solve a suitable real-world problem without prompting. This would be done by, over time, sequentially removing more and more questions on the template that are explicitly calling for the students to make decisions, leaving the students to choose which decisions to make when.

One of the strengths of this template is that it can serve equally well for instruction and to create detailed summative assessments of a person’s problem-solving skills in the respective discipline. The main difference is that for summative assessment, students would work to complete the worksheet alone without intermediate feedback. This would be useful both for assessing the skills of an individual student or the quality of an educational program by assessing skills of graduates of the program.

One challenge in most S & E instruction is achieving good alignment between instruction and assessment, even when following backward design. There are many examples in the discipline-based education research literature showing how students can do well on traditional exam questions in a course, but then do poorly on applying the concepts covered to simple novel situations (Kartal et al., 2016; Kim & Pak, 2002; Mazur, 1997; McDermott, 2001; Nakhleh & Mitchell, 1993; Pickering, 1990; Teichert et al., 2008). From a cognitive perspective, it is clear why there is a problem with alignment. The type of thinking required to solve a realistic problem encountered by a scientist or engineer is fundamentally different from what is required to do well on a school exam. In the former, the person discusses with colleagues what information is needed and how to go about solving the problem, consults references, and takes the time needed to come to a properly tested solution. In the latter, the student works alone with no access to any materials and under severe time pressure. There is no reason to think performance on the two activities should be well correlated. This challenge of alignment between instruction and assessment is reflected in the common criticism that an instructor is "just teaching to the test." We argue that optimum instruction should be doing exactly that, because the best instruction should have both exams and instruction fully aligned with the learning goals. The template for instruction (or assessment) proposed here achieves that goal.

Summary

Problem solving is the most important educational outcome for training good scientists and engineers. We have presented a novel theoretical framework for teaching complex problem solving in science and engineering, which will apply to teaching at every level of post-secondary education. The approach is deliberate practice of the decisions made by skilled scientists and engineers when solving problems. These decisions provide the necessary specificity about the components of skilled problem solving to teach more effectively and efficiently. We provide a template for teaching and assessing the full range of problem-solving knowledge and skills that a successful scientist or engineer needs to learn. We believe that this specificity and alignment of the learning goals, assessment, and instruction will provide more effective teaching of real-world problem-solving skills.

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