Promoting Critical Thinking during Problem Solving: Assessing Solution Credibility

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Abstract

Engineering students are considered novices while their instructors are experts in a given field. One of the goals of engineering education is to move students closer to being experts. Engineers are problem solvers by nature and an important skill to be learned is the ability to assess the credibility of solutions. Engineering educators can help students improve this ability by modeling solution assessment in the classroom by predicting, where possible, what the solution should look like before even solving a problem and then evaluating the result when it has been obtained. Some of the checks include the sign of the solution (positive or negative), the correct range and order of magnitude, the number of significant digits, and the error bars for laboratory measurements. The paper discusses problem solving, critical thinking, solution reality checks, and recommendations for how to implement solution prediction and assessment.

Introduction

Calls continue to be made for improving engineering education. The Phase 2 report from that committee titled *Educating the Engineer of 2020*[1] calls for the reinvention of engineering education. An important finding of that study was the importance of addressing how students learn in addition to what they learn and called for more research into engineering education. This includes how to determine pedagogical approaches that excite them. Duderstad recommended (2008, p. v) "a systematic, research-based approach to innovation and continuous improvement of engineering education."[2] Goldberg and Somerville (2014) advocated for a complete transformation of the engineering curriculum to meet the needs of today's engineering professionals.[3]

The ABET requirements for the 2015-2016 accreditation cycle[4] include several Student Outcomes related to problem solving. Outcome (a) includes "an ability to apply knowledge of mathematics, science, and engineering." That knowledge is typically used to solve problems. Outcome (e) includes "an ability to identify, formulate, and solve engineering problems." Outcome (k) includes "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice." This includes, for example, using computer programs to solve problems.

The specific problems of interest here are called *story problems*, which are those where a solution is developed from a shallow story context.[5] These are the most common form of problem solving, where students typically apply an appropriate algorithm to generate a quantitative answer. While much has been written on this subject, very little appears to have been written about considering valid solutions *before* attempting to solve the problem.

Engineering students normally learn how to become good problem solvers by the time they graduate. However, it is not generally clear those students have learned how to assess the validity of their solutions. This is a key skill they need to learn, preferably before entering the workforce. A personal experience demonstrated the importance of this skill. Early in the author's career in industry, another young engineer ran a computer analysis and sent the results to a client without first showing the solution to a more experienced engineer. It turned out the solution did not make sense, but the young engineer did not have enough experience to recognize that. This was embarrassing for both the young engineer and their company. This is also something that can be very frustrating for engineering educators when students produce nonsensical answers and don't know it. Engineering educators can facilitate the process of validating solutions by teaching students to constantly assess their results to make sure they pass reality checks.

Problem Solving

Problem solving is an important skill for professionals.[6] Problem solving may be one of the most fundamental processes for engineers.[7] Sheppard et al. (p. 3) wrote, "Engineering practice is, in its essence, problem solving."[8] Jonassen (p. 103) wrote, "Learning to solve workplace problems is an essential learning outcome for any engineering graduate. Every engineer is hired, retained, and rewarded for his or her ability to solve problems."[9] One goal of engineering education is to produce effective problem solvers. Roth and McGinn (p. 18) wrote, "Educating students to become problem solvers has been a goal of education at least since Dewey."[10] Jonassen (p. xvii) argued "the only legitimate cognitive goal of education (formal, informal, or other) in every educational context (public schools, university, and [especially] corporate training) is problem solving."[11]

Engineering students at graduation with an undergraduate degree are generally considered novices and do not become experts until they have had considerable experience. A key difference between experts and novices is how each approaches problem solving. Steif et al. (p. 135)[12] noted:

> By accurately representing the problem, the expert constrains the possible analyses or procedures to apply and can quickly and successfully solve the problem. By contrast, novices tend to immediately jump to some type of detailed analysis, often based on a poorly conceptualized and incomplete representation of the problem. As a result, they omit or mischaracterize key aspects of the problem and fail to successfully solve it.

Feedback is important in the process of learning and can be conceptualized as "information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one's performance or understanding."[13] For engineering students, a primary use of a textbook is to learn how to solve problems.[14] Unfortunately, the only feedback a textbook can give to a student is whether or not the final solution is correct or incorrect by checking the answer in the back of the book.

An effective technique for teaching students how to learn to solve problems is for the instructor to demonstrate the technique first and then to have students gradually replicate the process step-by-step.[15] This is referred to as a *worked-out example* which consists of problem formulation, the steps to the solution, and the final solution.[16,17] Some research has shown appropriately structured and worked-out examples can sometimes actually be more effective for learning than having students solve problems on their own.[18] Guided discovery is an effective technique for instructors to help students learn during the problem solving process.[19] Feedback during the solution process is particularly important for novices because it helps decrease their cognitive load.[20] Feedback (formative) throughout the problem solving process is more effective for learners compared to only receiving feedback after the problem has been solved (summative).[21]

Critical Thinking

The goal of most educational experiences is to increase the expertise of the learner. It is unlikely however that a student will become a true expert after completing a single class on a given subject. It normally takes a considerable amount of time and experience working in the subject area to become an expert. The knowledge of experts and novices differs both quantitatively and qualitatively.[22] Bransford et al. argued that merely accumulating information does not make someone an expert; rather it is a process of making domain specific knowledge relevant to problem solving strategies.[23] Instructors can help students "conditionalize" their knowledge by teaching them strategies to organize and apply that knowledge.

Brookfield defined critical thinking as finding our assumptions, testing their validity, seeing things from different viewpoints, and taking informed action.[24] Here, the concern is testing assumptions about valid solutions. Halpern (p. 450) defined critical thinking as "the deliberate use of skills and strategies that increase the probability of a desired outcome" which is specifically used in problem solving.[25] In this case, the desired outcome is the correct solution. Halpern argued students can become better critical thinkers through appropriate instruction and that enhancing students' critical thinking ability is both challenging and rewarding for instructors. Snyder and Snyder (p. 90) wrote, "students who are able to think critically are able to solve problems effectively."[26]

Critical thinking is a key metacognitive activity that should desirably occur during learning and problem solving.[27] Critical thinking and judgment are required for engineering professionals to solve workplace problems.[28] This includes the ability to critically evaluate the results of the solution to a problem. Merely generating an answer does not guarantee the result is credible and appropriate. In most university engineering courses, problems typically have a single correct answer that a student's answer can be compared against. Many real-world engineering problems are not that simple and often don't have a single correct answer. Students must develop the ability to critically assess their solutions for credibility since they will not be able to compare the results of solving real-world problems against an answer in the back of the book.

Reality Checks

There are a number of ways solutions can be assessed for validity including the sign of the result, the range of the result, the order of magnitude of the result, the number of significant digits, and measurement error. These all refer to critical thinking and reflection on the solution and are discussed next.

Positive or Negative

One important check of the reasonableness of an answer[29] is its sign. This is a gross error checking process that can be particularly important in certain subjects such as thermodynamics where there is a specific sign convention. Typically in thermodynamics, work done by a system is positive while work done on the system is negative and heat transfer into the system is positive while heat transfer out of the system is negative. This convention is used because normally the objective of a power cycle is to burn a fossil fuel (heat transfer into the system which is positive) to produce work out of the system (which is positive). Different devices in thermodynamics should produce results with a particular sign. For example, heat transfer for condensers is negative because they are removing heat, heat transfer for evaporators is positive because they are adding heat, work for a compressor is negative because it is added into the system, and work for a turbine is positive because it is produced by the system.

Students need to be familiar with the sign convention in a discipline so they can at least make sure their solution is the correct sign. In these types of problems, students should know even before starting the solution process what the sign of the answer should be. Instructors can reinforce this by discussing the sign of the solution before they begin solving these problems. After this has been demonstrated several times, the instructor can then ask students what the sign of the solution should be before the instructor begins to work out an example problem. In some problems there may be multiple devices and intermediate solutions where the instructor can demonstrate this process of checking results for reasonableness.

Correct Range

Another error check is to determine if a solution falls within the correct range. Most calculations have results that should be within a certain range to be valid. While some results can be either positive or negative (e.g., work and heat in thermodynamics), other results can only be positive. For example, calculating a negative mass does not make physical sense. For other types of results, the range is narrower than merely being positive. For example, thermal efficiency ranges between 0 and 100%. In thermodynamics, the quality of a fluid ranges between 0 (all liquid) and 1 (all vapor). Emissivity, absorptivity, transmissivity, and view factor in thermal radiation all must range between 0 and 1. Calculated results outside these ranges for those variables by definition do not pass the reality check. The credible range for certain types of solutions needs to be learned so students know if their results are at least plausible. Again, this can be demonstrated by the instructor by discussing possible solutions before working out an example and eventually asking students what are reasonable solutions before starting a problem. Final solutions can then be assessed to see if they fall within a valid range.

Order of Magnitude

Determining the appropriate order of magnitude for a result is often the most challenging for a novice. This type of knowledge usually only comes with a considerable amount of experience. The instructor can help students get a feeling for what are “reasonable” answers and what are not. A simple example in fluid flow relates to the difference between laminar and turbulent flow. If the flow is high speed, such as near or above Mach one, the flow will generally be turbulent as determined by calculating the Reynolds number. A common mistake students often make is not using the correct value for viscosity which may have a number in a table multiplied by a small number such as x 10^{-3}. If the student forgets to multiply by the small number, they can get a much smaller Reynolds number since the calculation includes dividing by the viscosity. This produces a result that can be off by orders of magnitude. Instructors should sensitize students to this type of mistake, especially to typical errors instructors commonly see, so students can make sure their results at least pass the order of magnitude check.

Significant Digits

While most engineering students are taught early in the curriculum about significant digits, they still seem to struggle with this concept even through graduation. Because a calculator or computer can generate many digits does not mean they are all significant. In most cases, only three or four digits are usually significant. Failure to recognize this either means students do not understand the concept of significant digits or are not disciplined enough to apply it. Some actually appear to believe the answer is better if they include more significant digits. Significant digits is an important concept that needs to be ingrained before starting full-time employment. A supervisor who is accustomed to working with real data will view results with too many significant digits as a poor reflection on the employee and probably on their alma-mater as well. Significant digits should be emphasized at the beginning of class. To show the importance, points may be deducted when too many significant digits are reported. One professor has decided that after attempting other ways to break students of reporting way too many digits, a point would be deducted on exams for each extra significant digit in a result.

The appropriate number of significant digits is something the instructor can discuss even before attempting to solve a problem. Based on the input data, students should be able to state how many significant digits are appropriate for the given problem. Rounding should not be done until the final solution to avoid round-off errors. When a result is computed, the instructor should specifically state how many digits should be used for the given problem. This reinforces the concept and indicates its importance.

Measurement Error

Students are normally taught about measurement error, but either fail to understand the concept or forget it when reporting results for lab experiments. Some seem to believe their measurements are much more accurate than they actually are. In many cases, university lab equipment may be old, outdated, and out of calibration. Experiments conducted in industry may be done to generate performance data, demonstrate the feasibility of a new technology, determine operating limits, or demonstrate compliance with permits and standards. In undergraduate laboratories, none of those are normally the objective which is usually to demonstrate a phenomenon or concept. Therefore, high accuracy is not normally an important consideration in most undergraduate university labs given the added time and cost that are usually required to get high accuracy. Unfortunately, results in lab reports seem to indicate otherwise where too many significant digits are often reported. Where possible, students should determine the estimated errors in their measurements so they can be reported accordingly. Failure to do so can imply the results are much more accurate than they really are. Error bars on the results provide a dose of reality for students about the potential inaccuracy in measurements. They may also help explain why experimental results sometimes do not follow theoretical predictions.

This exercise can be particularly valuable for those students who will be conducting experiments in industry. Not only will it give them an estimate of the accuracy of their measured results, but it can also indicate what specific measurements should be improved if they need higher accuracy. For example, it may be relatively easy and inexpensive to improve a temperature measurement, but it could be that for a particular experiment it does little if anything to improve the overall accuracy of the result. Maybe the mass flow rate has a much bigger effect on the results and that measurement is what should be improved. This is the kind of information that managers are looking for from engineers when making decisions.

Recommendations

Critical thinking is crucial to preparing engineering students for solving problems in the workplace. This includes asking questions. Snyder and Snyder (p. 91) wrote, "Instruction that supports critical thinking uses questioning techniques that require students to analyze, synthesize, and evaluate information to solve problems." Graesser et al. (p. S17) wrote, "questions are one of the fundamental cognitive components that guide human reasoning."[30] Asking questions is essential to problem solving.[11] Research has shown that good students are more effective at self-explanation during problem solving,[31] which includes asking questions. Questions help deepen thinking and understanding.[32] Instructors can encourage critical thinking as they demonstrate questioning during the problem solving process. Effective teachers teach students to use self-questioning to improve problem solving.[33] Collins referred to the process of an expert (the teacher) teaching an apprentice (the student) how to handle complex tasks such as problem solving as *cognitive apprenticeship*.[34] In assessing the validity of a solution, the instructor can teach the student to think about what the solution should look like both before and after solving a problem.

As more analyses becoming computerized, the ability to assess the credibility of solutions becomes even more important. Engineers need to be able to distinguish between reasonable and unreasonable solutions. While a primary function of engineering textbooks is often to teach problem solving, textbooks are not very conducive to promoting critical thinking about the solution during that process. In order to promote critical thinking, instructors should continually question students about the credibility of their solutions.

Instructors need to model critical thinking about, reflecting on, and assessing the validity of solutions, particularly during the introduction of new materials. Students cannot be expected to make critical judgments about something they know relatively little about.[24] Instructors should carefully explain their thought processes when assessing the validity of a solution. This can be demonstrated most effectively when the instructor gets an invalid solution while working out a problem because of an inadvertent mistake in the process. This can provide a "teaching moment" to show students even instructors make mistakes, but as experts they realize an error has been made so they know to go back through the process to find out what went wrong.

Once students have enough experience with a given type of problem and solution methodology, the instructor should ask students before even attempting the solution what they expect the answer to look like. Should it be positive or negative, within a certain range, or approximately a certain order of magnitude? What are an appropriate number of significant digits? When a solution is obtained, does it make sense?[11] If this questioning process is done consistently by the instructor, the goal is that students will learn to do this naturally whenever they are solving problems. They should predict something about the solution even before attempting to solve the problem. An added benefit is that instructors get feedback about students' level of understanding so they can adjust instruction accordingly. If students wrongly predict about the possible solution or wrongly assess the solution after it is obtained, then the instructor can address areas of misunderstanding.

Some of these concepts can be reinforced by the instructor in the place that students pay the most attention to – their grades. On assignments and exams, instructors can deduct points for too many significant digits and clearly invalid solutions. On the other hand, some credit can be given when a student gets a wrong answer and identifies it themselves. They understand they made a mistake somewhere but cannot find it (often because of lack of time if it is on an exam), because the answer does not pass the reality check. This is an important skill to be learned as novices journey towards becoming experts.

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