ASSESSING PROBLEM-SOLVING SKILLS

*Part I: The Context for Assessment**

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An analysis of the future of engineering education suggests that problem-solving skills are needed by today's graduates.[1] ABET Engineering Criteria 2000 criterion 3.e[2] asks that we show that graduates have skills in identifying, formulating, and solving problems. We define "problem solving" as the process used to effectively and efficiently obtain a best value for a goal or unknown for a given set of constraints when the pertinent data, the goal, and/or the method of solution are not obvious. This process is in contrast to "exercise solving" wherein the pertinent data, the goal, and the solution methods are quickly apparent because similar problems have been solved successfully in the past. It is a challenge to be able to distinguish between and appropriately assess a student's knowledge and comprehension, skill in exercise solving, and skill in problem solving. For ABET purposes (and to improve our educational efforts) we also want to evaluate the effectiveness of our programs in developing skill.

In this paper, we review the principles of assessment, list example goals and criteria for skill in problem solving, and list some options for assessing both a student's understanding of the subject knowledge and skill in problem solving. In Part II, (planned for publication in a future issue of *Chemical Engineering Education*) we will explore options for assessing the student's skill in problem solving, give evidence about the different options, and offer some suggestions for evaluating a program's effectiveness in developing skill in problem solving.

PRINCIPLES OF ASSESSMENT

We define "assessment" as a judgment based on the degree to which goals have been achieved using measurable criteria and pertinent evidence. We have found that breaking this definition into five principles assists in applying it. These five principles are as follows:[3-6]

* *Part 2, "Assessing the Process of Problem Solving," will appear in the next issue of* CEE.

▮ 1. Assessment is a judgment based on performance, not personalities. We need to help students realize that a poor mark does not mean that they are bad people. The judgment is made about performance in completing a task. This is an issue, especially for students with attitudes characterized by Perry's Level 2. More details about Perry's levels and their implications to teaching and learn-

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ing are given elsewhere.[3-8]

- 2. Assessment is a judgment based on evidence, not feelings. We might intuitively feel that a student is a good problem solver. We need to replace that intuitive feeling, however, with physical evidence such as the written script in an exam, a reflective journal, a self assessment, an assignment, or a project report.
- 3. Assessment should be done for a clearly identified purpose and with clearly defined performance conditions.
- 4. Assessment is a judgment done in the context of published goals, measurable criteria, and pertinent, agreed-upon forms of evidence.
- 5. Assessment should be based on multidimensional evidence:
  - *static and dynamic situations*
  - *small assignments and lengthy projects*
  - *academic, social, and personal contexts*
  - *a variety of conditions (*i.e., *exams and homework, written and oral presentations, performance as an individual and as a member of a group)*
  - *formative and summative data with different persons as assessors (*i.e., *self, peers, teacher, and trained external observers)*

ISSUES IN PRACTICE

To remove ambiguity from assessment, the following six issues in practice should be addressed.[3-6]

Goals

What is being assessed? Knowledge in chemical engineering? Skills? Attitudes? Have the goals been expressed unambiguously and in observable terms? Who creates the goals? Are the goals explicit and published?

Criteria

Are there criteria that relate to the goals? Can each criterion be measured? Who creates the criteria? Are the criteria explicit and published?

Form of evidence

What evidence is consistent with the criteria? Are the checklists used for the assessment asking questions related to the criteria? Do both the assessor and the student know that this form of evidence is acceptable?

Resources

Are the goals and the collection of evidence possible to achieve in the time and with the resources available?

Assessment process

What is the purpose of the assessment? Under what conditions is the student's performance assessed? Who assesses? What type of feedback is given by the assessor? (For example, pass-fail, a grade, five strengths and two areas to work on?) What is the form of the feedback? (For example, verbal or written?) What is the timing of the feedback? Who delivers the feedback?

Training in the assessment process

Have both the student and the assessor received training in assessment?

Failures of assessments to accomplish their purpose can usually be traced to violations of any of these five principles of assessment or to the incorrect application of the six issues in practice.

PUBLISH GOALS AND CRITERIA FOR PROBLEM SOLVING

Consistent with principle four, goals should be published to describe the target skills and attitudes of successful problem solvers. Although initially one might be satisfied with a general objective,[9] such as "skill in identifying, formulating, and solving problems," we have found it extremely helpful (especially for the purposes of assessment) to elaborate on the skill. Such elaboration should be based on research findings[10] about the performance of successful problem solvers. Here are some options for creating goals and criteria for problem solving.

Create a list of descriptors of the process

An example list could be: "The problem is defined, many issues and hypotheses are explored, the criteria are listed, and the issues are prioritized; the problem solver refrains from early closure and keeps at least five options open; active processes are used with continual and frequent monitoring (about once per minute); the approach taken is flexible yet organized and systematic; decisions are made based on criteria." A disadvantage of this approach is that few criteria are included. For example, without published criteria, what one assessor might judge to be "flexible performance," another might characterize as being "inflexible."

Create a list of target skills and attitudes

An example list of target skills for problem solving is available.[3,8,11] As with the previous approach listed, too few criteria are given.

Provide a structured list of goals, moving from beginning to advanced

Alverno College[5,12] identifies six levels of goals

- **Level 1.** Students are able to identify the process, assumptions, and limitations involved in problem-solving approaches. They are aware of the problem-solving process and are able to identify, order, and label the steps used in a strategy. They are able to state the assumptions or limitations involved and to identify or recognize the present situation, the desired goals, the pertinent knowledge and data, the constraints on the problem solver, any alternative plans, the total problem-solving process used, and the effective dimensions of the problem-solving approach. This awareness and ability will be demonstrated in three subject domains. The student is able to recognize common elements when the problem-solving process is used in different domains.

- **Level 2.** Students can recognize, analyze, and state a problem to be solved. This includes the ability to identify the type of problem, to determine the assumptions and constraints in the problem situation, to determine the information and time available to problem solve, to make explicit their own criteria, to recognize their usual style or approach, and to reformulate the problem as a result of a systematic examination of the previous dimensions.
- **Level 3.** Students can apply a problem-solving process to a problem. They can design and implement an entire problem-solving process to complete a project requiring new data from such sources as experiments, a synthesis of literature, surveys, and/or interviews.
- **Level 4.** Students can compare processes and evaluate their own approach in solving problems. They can repeat level three in another subject discipline. They can reflect on the process, identify their strengths and limitations as problem solvers, and compare processes used for the projects chosen in this level and in level three.
- **Level 5.** The students are able to design and implement a process for resolving a problem which requires collaboration with others.
- **Level 6.** Students demonstrate facility in solving problems in a variety of situations.

For each of the above levels, detailed and measurable criteria are published.[4,5,12]

List component skills and create sets of behavioral, unambiguous goals with measurable criteria for each

For example, in the McMaster problem solving program,[13] the three levels of development are

• *To be aware of and be able to apply skills to solve well-defined, ordinary homework problems and to extend those skills to solve problems in other courses and in personal life.* The component skills include awareness of the problem-solving process (or metacognition), systematic application of a strategy, ability to self assess and manage time and stress, facility in reading problem statements, and the development of an ease in classifying information. Those skills also include exhibiting creativity, defining the stated problem, creating goals and criteria, and creating the look back. Also needed is an ability to exploit personal preference, to translate information from one form to another (such as choosing symbols, drawing a diagram, formulating an equation), to get "unstuck," to learn and relate the pertinent subject knowledge to problem solving, and to explore the problem (or create the internal representation of the problem).

• *To solve problems as teams.* The component skills include conflict resolution, listening and responding, group work, chairperson skills, making decisions, and asking the right questions.

• *To be able to solve ill-defined or open-ended problems as individuals or as teams.* The component skills include defining problems, trouble shooting, lifetime learning, coping with ambiguity, and chairperson skills.

Each of the 30-plus component skills has about a dozen objectives, published measurable criteria, and example assessment tasks.[11,13,14]

We recommend the use of the last two options, from Alverno College or the McMaster problem-solving program, because assessment is easier (and more equitable and fair) with more explicit goals and published criteria.

FORMS OF EVIDENCE

Performance options to assess problem solving

Valid assessments are based on evidence (principles two and four). Selecting the various forms of evidence is a challenge because we want to assess both the quality of the *product or answer* and the efficiency and effectiveness of the *process* used to get the answer. Unraveling the process is not easy. The skilled process includes at least four components: subject knowledge, experience knowledge, past experience in solving similar problems successfully, and skill in problem solving.

• *Subject knowledge:* How well did the students comprehend the fundamentals of chemical engineering? Were the correct fundamentals chosen by the student? Students may fail to produce best answers because they don't understand the subject knowledge. As teachers, we have to provide students with opportunities to demonstrate problem solving using subject knowledge. Teachers should pose questions that give students a chance to demonstrate analysis, synthesis, and judgment (levels four to six in Bloom's taxonomy[15] in the cognitive domain).

• *Experience knowledge:* Some authors refer to this as "tacit knowledge," others refer to it as "rules of thumb." Typically, this memorized subject knowledge is concrete. For example, usually liquids are pumped at 1 m/s. This knowledge is crucial for judging if answers or assumptions are reasonable. For example, a student correctly used knowledge of heat exchange and optimization to yield an optimum heat exchanger of three tubes of length 4.3 km. A student should recognize that such a configuration is impractical and modify his answer. This experience knowledge is useful in judging reasonableness of numbers generated by simulators and computer programs.

• *Past experience in solving similar problems successfully and storing that experience for easy recall:* Usually, students are asked to solve problems on exams that are similar to those they have previously solved for homework. Indeed, in preparing for exams some students will have solved many other problems (from past exams, from other problems at the end of the chapter in the required text or other texts, etc.). If students have a rich set of accessible problem solutions, then the problems they encounter on the exam may be *exercises* and not *problems*. The skill they demonstrate will be exercise solving and not problem solving. The evidence we gather should be related to problem solving.

• *Skill in problem solving:* The goals and criteria were described earlier. One option researchers have to gather evidence about problem solving has been recording "protocols" of students solving problems. Such recordings can be made in written, audio, or videotaped forms.[10,16]

What we hope to measure and gather forms of evidence about includes a good answer (the product should be of value, the answer should be correct and reasonable) and a skilled process for achieving the answer to a problem (not an exercise).

Three general forms of evidence can be gathered—the correctness of the answer, a combination of the answer and the process, and, primarily, the process. In Part I, we describe seven options of evidence of the correctness of the answer and a combination of the answer and the process. In Part II, we will consider evidence primarily about the process and offer examples of how some of these options have been applied.

OPTION 1
Option for the Answer

The first option is to mark the answer. The answer should be marked on the basis of published, explicit criteria. This is an important form of evidence. The answer alone, however, tells us little about the efficiency and effectiveness of the problem-solving process used. Furthermore, as outlined in assessment principle five, many forms of evidence should be used. The evidence can be based on the final exam or on the term work that includes homework, tests, and projects. High marks in term work, however, might mean the students are knowledgeable about the subject matter and are good problem solvers, or it could mean the students copy and are neither. Low marks in term work could indicate a lack of subject knowledge, poor problem solving skills, lack of a source from which to copy, or lack of motivation.

Options for the answer and the process

For most assignments, tests, exams, and projects, teachers usually assess the problem-solving process as well as the answer. How well teachers can assess problem solving might depend on the teacher's response to the task and the student's response. The teacher's response includes assigning tasks that are "problems" and clarifying how problem-solving skills will be assessed.

Teacher's Response

- **The assigned task** should be an opportunity for the students to use higher-order thinking skills, such as analysis, synthesis, and judgment. But teachers tend to pose few such tasks. One analysis of a four-year curriculum, based on Bloom's classification, found that only 21% of the 2,952 homework problems assigned were level four to six.[17-18] For creating exams, one guideline suggests that at least half of the marks should be assigned to questions demanding higher-order thinking. Another recommends that at least three questions out of eleven test higher-order thinking.[19] Traditional examinations usually contain a limited number of questions testing problem-solving skill. If the teacher wants to use a separate "mark for problem solving," he can average only the marks for those questions testing higher-order thinking skills.
- **Clarifying** how problem solving will be assessed is also part of the teacher's response. Exam marks are a mix of having the correct answer and the individual instructor's version of how to assign part marks for subject knowledge comprehension and the problem-solving process. The teacher's script to mark the problem solving should be published and based on research evidence such as the "novice versus expert" data[10] for problem solving instead of on the teacher's intuition and personal style. For example, students should know that they are expected to list five hypotheses, identify criteria, write down monitoring statements for each minute of thinking, and select the best hypothesis.

  Documentation such as the monitoring statements should help clarify the process of assigning the part marks, but this is still not easy. We analyzed the part marks given for different types of questions on an exam in a senior course (sample size, n=43). The sample size is small, but the findings illustrate the difficulty teachers have in marking the problem-solving process in conventional examinations.

  For an application question (Bloom's level three), twelve students lost marks because they didn't show they understood the chemical engineering knowledge, three lost marks because of mathematical mistakes, six lost marks because they did not provide sufficient detail and/or rationalization of how they did the calculations, and one lost marks because he misread the problem. Twenty-one received full marks.

An analysis-synthesis question (level four to five) on the same exam in the same course resulted in six students losing marks because they did not detect simple errors, and 22 lost marks because they failed to address all the issues given in the problem statement. The assessor could not distinguish from each student's written work whether that student did not understand the knowledge or whether his problem-solving skills were deficient.

Student's Response

- **Is the task a "problem" or an "exercise?"** Have the students seen a similar situation before and are they recalling a past practice? For exams, for example, the top students probably worked so many problems from past exams that many exam questions may be exercises to them but are problems for the C, D, and F students. If our goal is to assess problem solving, then we should assess problem solving and not exercise solving. More comments about problem solving versus exercise solving are available.[20]
- **Exam anxiety**[21-23] may interfere with the students' performance. Our data indicate that some students suffering from exam anxiety have exam marks 20% to 35% below our assessment of their ability.[22] Students with exam anxiety might be identified with the use of the Alpert-Haber anxiety achievement inventory[21] or from high scores on the Kellner-Sheffield inventory.[22,23] We found that students with high scores on both of these inventories also had exam marks that were more than 30% below their term work mark. This might serve as an indicator of exam anxiety when data from either of these inventories are missing. This could also be a measure of academic dishonesty, but for the purpose of this work we assume it measures exam anxiety.
- **Student motivation and skill in taking exams** should also be considered. Students may not perform well on written exams because they lack motivation or they are unskilled in studying for tests. Two possible indicators of motivation might be using the elements "attitude" and "motivation" in LASSI[24] or hypothesizing that unmotivated students hand in less than 50% of the term work assignments. Skill in studying for tests might be measured by the elements "study for tests" and "test strategy" from LASSI[24] or by a measure we developed.[22]
- **The student's inability to display the process** has to be taken into consideration. Our experience has been that students rarely display their problem-solving processes explicitly on exams. Their written scripts often omit important mental processing that they use. One of the challenges is to help the students make the process visible as evidence.

Options two through seven try to address this latter issue by encouraging the student to make the problem-solving process visible. These options include

- *Telling them the process is important*
- *Offering guidelines about the key processing features*
- *Prompting them by requiring them to use a problem-solving template*
- *Making the process steps explicit choices*

OPTION 2
Tell Students the Process is Important

In a variety of chemical engineering test questions, mark the student scripts of solutions for the comprehension of the subject matter, correctness of the answer, and the problem-solving process displayed. This is easier said than done. Telling them marks will be given for the process is often too little instruction. Furthermore, this approach usually fails to use assessment principle four. The criteria for marking the problem-solving aspects of the script are usually unpublished and intuitive approaches chosen by the instructor. This approach could have potential.

OPTION 3
Give Guidelines About the Key Problem-Solving Elements

This differs from option two in the explicitness with which the criteria and purpose are presented to the students. In tests, assignments, and examinations we can give marks for process with a marking scheme that might assign, for example, five marks for a correct definition of the problem, fifteen marks for a correct diagram and identification system, five marks for the selection of the correct theory and equations, three marks for the correct identification of the boundary and initial conditions, and so on. The "correctness" is judged by the teacher. Heller, *et al.*,[25] used this approach in their study of problem-solving skill development in the context of freshman physics.

The scheme they used was to mark

- *The degree of conceptual understanding of the physics of the problem.* Does the description of the physics show that the student clearly understands the physics and relationships?
- *Whether the student's description of the physics was useful.* Is the description correct? Is it complete? Are all the correct forces shown? If the question is about forces, are forces shown on the diagram?
- *Whether the equation matched the physics description.* Are the correct equations used?
- *Whether a reasonable plan for solution was displayed.* Does the solution show that the number of unknowns equals the number of independent equations? Are the

equations solved in the correct sequence?

• *Whether a logical mathematical progression was used to arrive at the solution.* Did the student identify the correct general expression and correctly reduce it to the form specific for this application? Did the student delay substituting with numbers until the unknown variable had been isolated?

• *Whether the student used appropriate mathematical procedures.* Is the mathematics reasonable? Are the assumptions reasonable? Is there a correct mathematical method of solution? Correctness was judged by the teacher.

Such marking schemes for problem solving tend to be specific to the context (in this case, to physics) and this example is an interesting mix of issues related to subject knowledge comprehension (the first three listed) and to problem solving. For these items the student could lack either knowledge or problem-solving skills. Discrimination is difficult. This scheme addresses analysis (as described in Bloom's level four). Different schemes would have to be created for problems asking for synthesis, reasoning, evaluation, and for different subjects.

Whereas this example is specific to physics, marking schemes that are less dependent on the context have been used. For example, the creators of the PRIDE program[26] developed and used the Cognitive Objective List-Assisted Report Scoring (COLARS) scheme. The criteria used were number and quality of the citations, summary, transformation of information, application, analysis, synthesis, and evaluation. COLARS was used to assess student project reports. The criteria consider a combination of writing, research, and general higher-level thinking skills. These criteria can be made more specific through the use of the novice versus expert evidence for problem-solving skill.[10] Without such detail, the expectations and assessment are ambiguous, especially for students. For this approach to provide useful evidence, the third and fourth assessment principles need to be addressed. The performance conditions should provide students with an opportunity to present pertinent evidence. The goals and criteria need to be defined and published.

Angelo and Cross[27] describe a similar option, CAT 22, and use it to monitor the classroom learning experience. CAT 22 could provide evidence for assignment if the criteria are published and are consistent with the goals, as described in section two, and if the students are aware of the goals and the purpose of the activity.

OPTION 4

Prompt Students by Requiring the Use of a Problem-Solving Template

Teachers can provide a template to be used by students as they solve problems.[28,29] Mettes, *et al.*,[28] provide a list of the numbered phases, with details, on the left-hand side of the page with working space to the right where students are expected to show their work keyed to the number of activity. For example, Phase 1 is "analysis," which has the sub-activities of

- *1.1 Read and mark*
- *1.2 Sketch or scheme the data*
- *1.3 Reword what is asked*
- *1.4 Estimate*
- *1.5 Give the overall picture*

Heller and Heller[29] have five overall phases

- *Focus the problem*
- *Describe the physics*
- *Plan the solution*
- *Execute the plan*
- *Evaluate the answer*

Trigger words for these phrases are printed on two pages with plenty of space around each set of words where students can write their work. Both of these templates are structured around a problem solving strategy.[28,29] The use of this particular option offers advantages and disadvantages.

On the positive side, the use of such a format helps students develop elements of the target skills. In this case those skills are being systematic and organized, being able to select the appropriate cognitive and attitudinal skills, and being able to overcome the initial panic they might have when faced with a difficult problem to solve. Such a script usually provides many more details of the process than are given by students working under the conditions of options one through three. The script is usually easy to mark and we believe it provides valid evidence since this is consistent with some of the target skills.

On the negative side, successful problem solvers rarely apply the stages serially.[3,10,15,20,30] They do not define, then explore, and then plan. They cycle back and forth among stages *as they need them* with frequent rereading of the problem statement. Hence, the very use of the structured form, especially if the stages are numbered serially, tends to impede the development of other skills important in problem solving, such as the flexible use of a strategy.[20] This option is easy to mark but focuses on a restricted set of problem-solving skills.

Angelo and Cross[27] describe CAT 21 to monitor the classroom learning experience. CAT 21 could provide evidence for assessment if the criteria are published and consistent with the goals, as described in section two, and if the students are aware of the goals and purpose of the activity. Indeed, one of the templates suggested above might be used to enrich CAT 21.

OPTION 5
Make the Process Steps Explicit Choices

Barrows[31] created the Portable Patient Problem Pack (P4) to assess knowledge and problem-solving process skill for medical students. In this approach, students select cards, one at a time, and give their preferred sequence of problem-solving activities. On the front of each card is printed a problem-solving activity. Students learn the results by reading the back of the selected card. The sequence of cards selected and the rating for each card provide evidence about the problem-solving process. Each card has a printed rating based on the use of the P4 deck by skilled problem solvers.

Barrows created a set of cards that simulate the clinical interaction between a doctor and patient. These cards outline the following stages:

- *The situation (single card)*
- *History to be gathered from the patient*
- *Questions to ask the patient*
- *Actions, as in physical examination and laboratory tests to be performed*
- *Consultants brought in*
- *Interventions, both medical and nursing*
- *Closure (single card)*

The P4 method has been developed for medical programs, but a P4 deck could be developed in other subjects. For example, Munn, *et al.*[32] created a P4 deck for the alleged environmental impact of effluent from a pulp and paper company.

OPTION 6
Make the Process Steps Explicit (TRIPSE)

Rangachari[33] developed the following assessment activity to be used with one teacher and classes of up to 20 students. He asks students to resolve a set of data. The task is divided into three stages with students providing written evidence from each stage. He called the activity "Triple Problem-Solving Exercise" or TRIPSE.

In the first phase, within thirty to forty minutes, students write an explanation/hypothesis for the data they are given. Data are from experimental, clinical, or field settings in the context of undergraduate pharmacology or epidemiology. In the second phase, within thirty to forty minutes, students select one of their explanations and design one or more experiments or provide avenues for further exploration in relation to the chosen explanation. In the final phase, students are given feedback information and asked to reevaluate their original explanation or tests in the light of the new information. Students are assessed on all three tasks.

OPTION 7
Make the Process Steps Explicit (Triads for Trouble Shooting)

Troubleshooting problems are created in the context of the chemical process industry. Accompanying each problem is the "expert system" that describes the cause, gives the results of various diagnostic tests, and suggests how to respond to the requests of a troubleshooter. A separate guide[13] summarizes the target skills of effective troubleshooters,[34-43] gives a feedback form based on research evidence of expert behavior,[34-43] and provides a worksheet for the troubleshooter to use in posing tasks.

The triad consists of a troubleshooter, an expert system, and an observer. Before the activity, each person is given a set of problem statements, expert system details for his case, and the troubleshooter's guide material with feedback forms. In a ninety-minute period, each person assumes each role. The activity starts with the first expert system handing the problem statement to the troubleshooter. The troubleshooter reads the problem aloud, talks about his thought processes, writes on the worksheet questions, tests calculations, and consults on tasks to enable him to identify, correct, or minimize the fault. The expert system responds in writing to each request. Only one request can be made at a time.

Throughout the activity, the observer completes the feedback sheet regarding the quality of the problem-solving process used by the troubleshooter. Thus, after each person has played all three roles, each person also has written evidence about the questions and answers (from the worksheet) and feedback about the process used (from the observer's sheet). This approach has been used with classes of up to 100 and for engineers in industry, and since the groups work autonomously the only limitation is creation of the case materials.

Eight other forms of evidence, which focus primarily on the problem-solving process, will be given in Part II.

SUMMARY

The five principles of assessment provide a framework for developing and using instruments for assessment of student performance and of the evaluation of program effectiveness. Crucial to any assessment is the creation of published goals and measurable criteria that form the context for the performance of the student. Evidence should be gathered and assessed in the context of these goals and criteria. Four example sets of goals and criteria were presented.

Assessment is based on evidence of performance. Seven options of gathering evidence were described in this paper. Eight options that focus more on measuring the problem-solving process will be given in Part II. The first two options of evidence (mark the answer and tell the student the process is important) provided exam scripts in subject discipline, where correctness of the answer, subject knowledge, and problem solving were being marked. We elaborated on the challenges of using conventional exams as a measure of problem-solving skill.

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