AC 2009-653: DEVELOPING A RUBRIC TO ASSESS CRITICAL THINKING IN ASSIGNMENTS WITH AN OPEN-ENDED COMPONENT

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Keywords: Critical Thinking, Rubric, Open-Ended Problem Solving

Abstract

The ability to think critically is vital to success in engineering and technology practice. Employers in these fields, however, consistently identify critical thinking as one of the skills that is not sufficiently developed in new college graduates, and call upon engineering and technology educators to address this obvious need. Unfortunately, critical thinking is a developmental skill that cannot be taught simply by the usual methods – step-by-step instruction followed by repetitive drills – used for other technical skills. Critical thinking must instead be nurtured through practical experience solving problems with appropriate guidance and reinforcement. One very effective context for developing such skills is in open-ended assignments with no single "right" answer, to which students must apply not only their technical knowledge, but also an element of critical judgment, to determine which approach among many possible will yield the most reasonable and applicable results.

For educators, a key component of nurturing critical thinking is learning to recognize and reinforce it when it happens, or nudge students toward such behaviors when it is not happening but should be. Toward that end, we have developed a rubric to assess critical thinking during several phases (initial design or set-up; testing of method; evaluation of results) of open-ended assignments in engineering and technology. The rubric is designed to be generally applicable to open-ended assignments at every level (freshman through senior) in engineering and technology, allowing users to track the development of critical thinking skills as students progress through the curriculum. We present the rubric and preliminary results from applying it to two different open-ended assignments.

Introduction

Critical thinking, the ability to analyze carefully and logically information and ideas from multiple sources, is a vitally important skill for practicing engineers and technologists. Engineering problem-solving in real-world settings requires navigating complex and sometimes contradictory information, synthesizing conflicting goals into an attainable set of requirements, and evaluating and choosing among multiple possible approaches even when there is not a clear "best" path forward. Yet critical thinking is among the skills employers most frequently identify as lacking in new graduates[1]. Moreover, the 2006 National Survey of Student Engagement revealed that at least at IUPUI, engineering and technology students identified critical thinking as a slightly (but statistically significantly) smaller component of their educational experiences than students in other disciplines[2,3].

Clearly, fostering critical thinking in engineering and technology education will improve these outcomes. A previous study[3] surveyed the educational literature, with a particular focus on science, technology, engineering, and mathematics courses and programs at the undergraduate level, to determine current best practices in critical thinking for engineering and technology education. The two major themes that emerged for exercises targeted to the course level were open-ended problem-solving assignments with no clear-cut "right" answer or approach, and written assignments with a reflective component, frequently requiring judgment in the face of uncertainty. Table 1, taken from this previous study, summarizes the relationship between the steps of problem solving[4] and the components of a complete act of thought as proposed by Dewey[5]. Dewey's work forms the foundation for current literature on critical thinking.

Problem Solving	**Complete Act of Thought**
1. Define the problem	(i) a felt difficulty
	(ii) its location and definition
2. Explore a variety of solutions without limiting ideas (at this phase)	(iii) suggestion of possible solutions
3. Determine 'best' solution using a pre-defined analysis technique	(iv) development by reasoning of the bearings of the suggestion
4. Plan and implement the solution	(v) further observation and experiment leading to its acceptance or rejection; that is, the conclusion of belief or disbelief
5. Evaluate results	

Table 1 Comparison of Problem Solving and a "Complete Act of Thought"

It is not enough, however, simply to add to the curriculum assignments that draw upon critical thinking skills. A tool for assessing those skills is also necessary, to provide both guidance to students on their current skill levels and what they can do to improve, and feedback to instructors on their students' capabilities, areas of weakness, and progress. To that end, we have developed a rubric to assess students' developmental progress in critical thinking as applied to the steps of the problem-solving process. The current study summarizes the development of this rubric, its application and utility, and the results of applying it to open-ended assignments in two different courses (one in Electrical Engineering Technology, one in Biomedical Engineering).

Methods

Choosing Critical Thinking Assignments

Critical thinking requires students to analyze carefully and logically information and ideas from multiple perspectives. That is a complex requirement, and therefore the assignments to practice critical thinking will also be complex. According to the literature[3], most assignments take one of two forms: reflective writing or solving open-ended problems. Since this project focuses on critical thinking in engineering and technology, solving open ended problems is a natural fit: problem solving is an objective of all accredited engineering and technology programs[6,7]. Many programs and courses require some type of design or project that asks students to define a problem, pose possible solutions, select the "best" solution, then implement and test their solution. These types of projects may be done in a group or individually, and may be done in a lab period, over the course of several weeks, or be structured as a capstone experience.

Instructors usually observe the results of students' work and evaluate projects based on the specifications provided at the beginning of the assignment. As important as it is for students to meet the stated criteria, it is difficult to evaluate students' critical thinking when only seeing the end result of the process. Critical thinking is a reflective process; to assess it, we must "get inside the student's head". Students must self report what their thought processes were and that must be done in the narrative form - either orally or in writing. For convenience and assessment documentation purposes, having students write a reflective paper is good way to communicate their critical thinking.

Thus, our model critical thinking assignment asks students to solve some open-ended problem, and then write a brief description of the process they used.

Existing Critical Thinking Rubrics

Critical thinking rubrics are available from a variety of disciplines. An excellent source is Opened Practices (http://openedpractices.org)[8], which allows for reuse under a Creative Commons Attribution-Noncommercial-Share Alike 3.0 United States License; several examples are listed in the references[9-12].

Because of the nature of engineers and technologists, and our desire to accurately describe any areas of weakness, we concentrated on analytical rubrics that evaluate aspects of problem solving separately, rather than assigning a holistic score to the entire process. (Examples of the two types of rubrics are available from Valencia Community College[11,12].) If our focus was critical thinking in writing, our approach may have been different. For the proposed critical thinking assignments focusing on problem-solving, however, an analytical rubric based on the five steps of problem solving as presented by Cloete[11] will be more effective for both educating and assessing students in critical thinking.

Rubrics vary in the number of levels of competency delineated: three, four, and five are common, although as many as many as six are workable[9]. Given the opportunity, evaluators often rate in the middle, rather than commit to one "side" or the other. By forcing the evaluator to choose one of four levels, the assessment results are more reflective of true student abilities and avoid the natural tendency to cluster at the middle, "average" rating.

Another desirable feature of rubric criteria is a unique, descriptive term to describe each level of achievement for each category of evaluation. This provides a short "handle" to use for a condensed format of the rubric. It is an asset when training evaluators and when explaining the rubric to students. It is also convenient when automating the rubric in an on-line environment: by giving a unique description to each cell in the rubric, the evaluator is less likely to get confused on which category or level is being selected.

Critical Thinking Rubric for Engineering and Technology Problem-Solving

Drawing on examples from the Opened Practices database[8-12], we developed a rubric (Table 2) to assess critical thinking in Engineering and Technology assignments. The rubric targets problem-solving by breaking the process into five steps: defining the problem, proposing methods of solution, selecting the most appropriate method, applying the method to generate results, and drawing conclusions. Performance on each of these steps is assessed at one of four levels: Beginning (student work shows little evidence of independent or critical thought); Developing (student shows some awareness of the steps of critical thinking and problem solving, but applies them superficially); Competent (student work shows facility with the problem-solving process, but may miss subtleties); and Accomplished (student demonstrates deep understanding not only of the problem-solving process, but also of the pitfalls of the solution and of other possible approaches). These levels reflect the natural development of critical thinking skills with time and practice, with "Beginning" reflecting typical pre-college work and "Accomplished" the expected level of a practicing engineering or technology professional with significant problem-solving experience. Keywords in each cell show at a glance what each level of performance looks like at each problem-solving step, with more detailed descriptions providing additional guidance.

The rubric, thus designed, meets several goals:

The rubric targets the steps of problem-solving. It is not geared toward a specific assignment, but can be applied generally to any assignment with an open-ended problem-solving component. Therefore, it can be used across disciplines. Furthermore, because the individual steps of problem-solving are assessed individually, use of the rubric may uncover the parts of the problem-solving process with which students are particularly proficient or struggling, both individually and in the class as a whole.

The rubric is applicable not only across classes, but also across levels. Because it is targeted generally to the problem-solving process rather than to a specific assignment, the rubric is appropriate for any assignment – in any class – that includes an open-ended problem-solving component, including laboratory and design-oriented assignments. Moreover, the rubric can be used to track the development of critical-thinking skills as students progress through the curriculum. It is not expected that a freshman – or even the average senior – will score at the "Accomplished" level. Rather, instructors must decide what level of performance is reasonable for students in their class, and assign grades accordingly: freshmen may be expected to perform somewhere between the "Beginning" and "Developing" level, for example, with seniors expected to perform consistently at the "Competent" level. Applying this rubric to assignments at multiple points in the curriculum allows direct comparison of critical-thinking skills for students at different academic levels.

	Beginning	Developing	Competent	Accomplished
Defining the Problem	Indiscriminate Takes problem as stated without regard to relevance. (repeat what is “true but not useful”)	Obvious Determines what is relevant & what is not	Complete Gives voice to what other information is needed to solve problem	Complex Identifies and clearly states both the main question and subsidiary, embedded, or implicit aspects of the question
Proposing Multiple methods of Solution	Singular Names a single solution, position, or perspective, often inaccurately, or fails to present a solution, position or perspective	Dualistic Identifies simple solutions, over-simplified positions, or perspectives with minor inaccuracies	Multiplistic Describes two or more solutions, positions, or perspectives accurately	Balanced Explains—accurately and thoroughly—multiple solutions, positions, or perspectives that balance opposing points of view
Selecting the Most Appropriate Method	Inappropriate Provides a solution that does not meet the specifications required	Reasonable Presents a reasonable solution, but does not justify or clearly articulate that solution. No discussion of alternate approaches included	Relevant Clearly articulates design of solution. Some discussion of basis in data and/or theory is present, but not thorough. Provides some justification for approach, but does not acknowledge that other possibilities are feasible	Insightful Clearly articulates design of solution, and draws on data and/or theoretical basis, as appropriate. Acknowledges that other approaches may be feasible, and provides justification for the method chosen
Applying Method to Generate Results	Inaccurate Labels formulas, procedures, principles, or themes inappropriately or inaccurately, or omits them	Appropriate Uses appropriate formulas, procedures, principles, or themes with minor inaccuracies	Accurate Applies formulas, procedures, principles, or themes appropriately and accurately in familiar contexts	Thorough Employs formulas, procedures, principles, or themes accurately, appropriately and/or creatively in new contexts
Conclusions and Evaluation	Illogical Attempts a conclusion or evaluation that is illogical or inconsistent with evidence presented, or omits a conclusion or solution altogether.	Reasonable Presents abbreviated or simple conclusions that are mostly consistent with evidence presented, with minor inconsistencies or omissions	Logical Clearly states and discusses conclusions. Organizes a conclusion or solution that is complete, logical, and consistent with evidence presented	Perceptive Clearly states and discusses conclusions. Considers implications and consequences of the conclusion in context, relative to assumptions, and supporting evidence. Provides reflective thought with regards to the assertions

Table 2: Critical-thinking rubric for open-ended problem-solving assignments

The four-point scale provides an appropriate level of gradation. One of the most challenging aspects of designing a rubric is deciding on an appropriate scale by which to assess achievement. The scale should provide sufficient discrimination among obviously different levels of performance, but should not be so fine that it becomes challenging to decide between subtly different levels. Part of the utility of a rubric, after all, is its ease of application. For this reason, three to five levels is generally recommended[13]. A four-point scale both provides sufficient gradation and eliminates the tendency to gravitate toward the middle score – an assessment that "this work is average" – as happens in rubrics with an odd number of performance levels.

Results

Electrical and Mechanical Engineering Technology

ECET 351, Instrumentation Applications for Technology, is a junior level course. It is required for mechanical engineering technology majors, but may be used as an elective for electrical and computer engineering technology majors. In the fall semester of 2008, there were 25 students; approximately 2/3 were MET majors, and the remaining 1/3 were ECET majors. The students were assigned to five mixed-major teams and each group was given a different instrumentation and control project. The projects were open-ended; many of the projects required the students to "do something cool" with the assigned hardware, with only minimal specifications given. Students were informed that grades would be assigned based on the process – i.e. the design didn't have to work for a good grade, but the team *did* have to be productive. Along with demonstrating their group's projects to the class, each individual student was asked to write a one to two page reflection piece on the project. The rubric was distributed to the students at the time of the assignment, and students were informed that they should aim to demonstrate a level of "Competent" for each criterion.

The rubric was used to evaluate every student's work as presented in the reflection paper. The results are presented in Figure 1. The desired outcome was for students to demonstrate competent or accomplished behavior for all five steps of the problem solving process. They were most successful in "Applying Method to Generate Results"; this is to be expected, based on the emphasis placed in many lower level courses in step-by-step problem "solving". ("Just tell me what to do, and I'll do it!") Students had more difficulty in "Defining the Problem" and "Selecting the Most Appropriate Method." The worst performance was in "Proposing Multiple Methods of Solution" due to many students presenting only one solution – the solution that was implemented. The implications of these results will have to be decided by faculty.

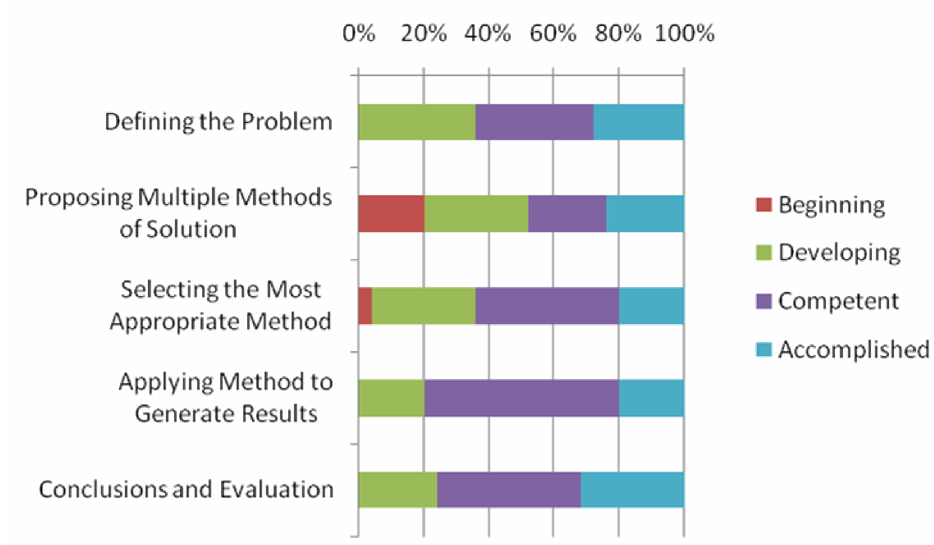

Figure 1: Rubric Results from Instrumentation Project Reflections

As a first step toward validating inter-reviewer reliability of the rubric, two student submissions were also rated by a second reviewer. Table 3 shows the results of these scorings; for ease of interpretation, the numbers 1-4 are used to represent scores of Beginning, Developing, Competent or Accomplished, respectively. Of ten scores assigned, six were identical between the two reviewers; in the other four cases, scores were off by one category only (Tables 3 and 4). Furthermore, the two reviewers showed strong agreement in whether skills were being demonstrated at a higher level (3 or 4) versus a lower level (1 or 2). This latter result may reflect the clear difference in overall quality between these two papers rather than any property inherent to the rubric, however.

	Skill	Reviewer 1 score	Reviewer 2 score
Paper 1	Defining the Problem	3	3
	Proposing Multiple Methods of Solution	4	3
	Selecting the Most Appropriate Method	4	3
	Applying Method to Generate Results	3	4
	Conclusions and Evaluation	3	3
Paper 2	Defining the Problem	1	2
	Proposing Multiple Methods of Solution	1	1
	Selecting the Most Appropriate Method	2	2
	Applying Method to Generate Results	1	1
	Conclusions and Evaluation	2	2

Table 3: Scores assigned by two reviewers

Cohen's kappa[14] was calculated to quantify the degree of inter-relater reliability (Table 4). This small sample gives a Cohen's kappa of 0.4595 (p=0.0214), indicating moderate overall agreement.

		Reviewer 1			
		Beginning	Developing	Competent	Accomplished
Reviewer 2	Beginning	2	0	0	0
	Developing	1	2	0	0
	Competent	0	0	2	2
	Accomplished	0	0	1	0

Table 4: Inter-relater reliability data

Biomedical Engineering

Students in a required Junior-level course, Probability and Applications in Biomedical Engineering, were given an assignment to model the probabilistic behavior of a potassium ion channel using MATLAB (and taking advantage of the built-in random number function). Students were then to simulate whole-cell potassium current by summing up the current generated by an appropriate number of these individual ion channels. Data on average channel density and average ion channel current were provided from the electrophysiology literature. Students were already somewhat familiar with expected whole-cell ionic current: an assignment in the previous semester explored the (deterministic) Hodgkin-Huxley model of current and voltage in the squid giant axon, and a version of that model was provided with the probability assignment for comparison.

The assignment was open-ended in that students had to decide for themselves what aspects of whole-cell current trajectory were most important to match with their probabilistically-based models, as well as what approaches to take in model development in order to ensure that they captured that behavior. Furthermore, blind application of the numbers from the literature resulted in total whole-cell current well below that produced by the deterministic model. Students needed to think critically in order to figure out what assumptions needed to be re-examined in order to explain those differences.

The assignment, from Spring 2008, was originally graded with a less-well-developed rubric that considered model design and testing, evaluation, and writing structure and content, each assigned a score on a scale from 1-10. Because there was too fine a gradation in scores without any description of the level of performance expected for each score, this rubric was difficult to apply. Applying the new critical thinking rubric to the same assignment not only was much easier, it produced final scores well-correlated to the original grades (Figure 2, R^2=0.846). Correlation of the new rubric with just the design, testing, and evaluation portions of the old rubric was also strong (R^2=0.838).

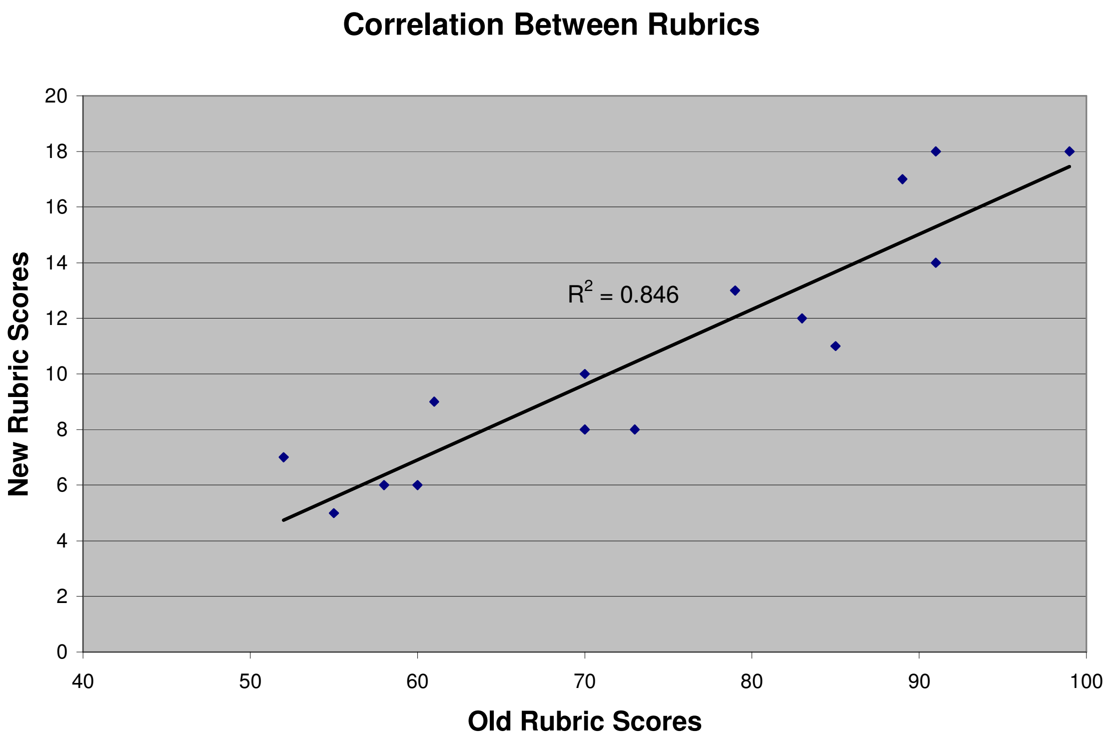

Figure 2: Comparing overall assignment scores using the new and an older rubric

Students in this Junior-level class scored on average between 2 ("Developing") and 3 ("Competent") on most steps of the problem-solving process (Figure 3). The major exception was the "Conclusions and Evaluation" section, with an average score of 1.6. Many students confessed that they had left this assignment to the last minute, and while they had done a good job modeling the system, they did not leave themselves enough time to write up all of their observations and conclusions. In addition, slightly lower average scores on "Proposing Methods of Solution" (average 2.2) and "Applying Method to Generate Results" (average 2.2) reinforced observations from instructors of our program's Senior students that our students do not understand the process of writing requirements and using them to guide the design and testing process. Both of these weaknesses are being addressed in the Spring 2009 session of this course: students will go through a separate exercise in requirements-writing before confronting this assignment, and the assignment itself will be due earlier in the semester, with an opportunity for re-writing and re-submitting after peer feedback. The critical thinking rubric will help to assess what effects, if any, these changes make in student performance on this assignment.

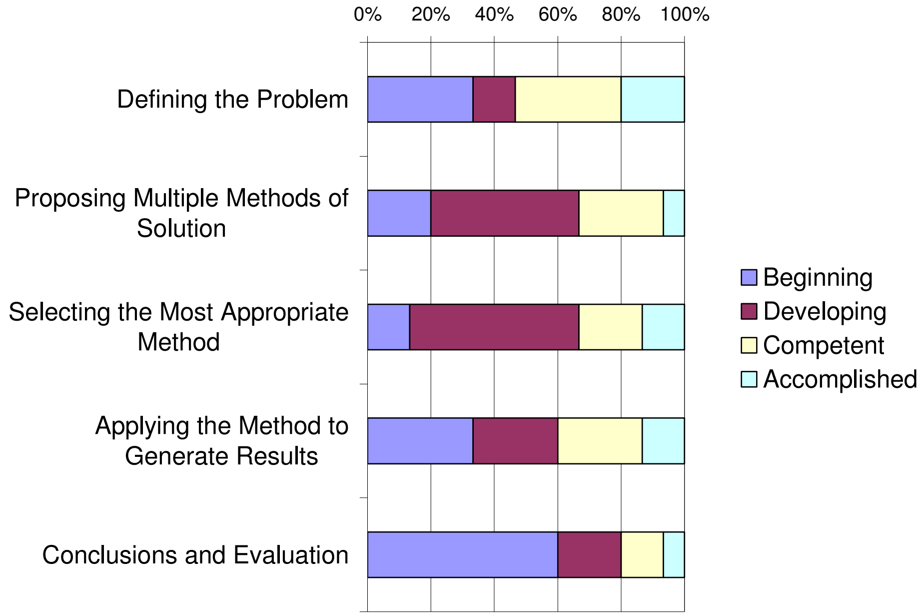

Figure 3: Rubric results from Biomedical Engineering modeling assignment

Discussion and Conclusions

Students seemed to perform a bit better overall according to the rubric criteria when the rubric was made available to students along with the assignment (as was the case with the ECET assignment). In future semesters, the rubric will be supplied along with the BME assignment to see whether these differences in performance can be quantified more directly.

Although preliminary results indicate reasonable inter-reviewer reliability, more work is needed to verify and quantify reliability. In spring of 2009, additional faculty will be trained to use the rubric and inter-rater reliability will be studied. Training will include group discussions of each criterion, and application of the rubric to an example work. After completing this first evaluation, faculty will share and discuss their ratings and build consensus on appropriate levels of performance. They will evaluate a second example and results will be used to further verify inter-rater reliability.

Based on the results of applying this rubric to two open-ended assignments in two different departments, and comparing the results with a previous assessment on one of these assignments, we conclude that the new rubric is well-suited to assessing student work on open-ended assignments. It can be used to grade student work more quickly than previous rubrics. It is appropriate to open-ended problem-solving assignments in any discipline, and can be applied at any undergraduate level. It reveals specific parts of the problem-solving process in which students (individually or as a group) need more guidance and practice. Finally, it may provide an important tool for program assessment by providing data on the development of critical thinking skills as students progress through the curriculum. It may also be used to measure the effectiveness of changes meant to improve critical thinking-related exercises in a single course from one semester to the next.

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