Developing a Method to Measure the Metacognitive Effects Of a Course on Design, Engineering and Technology over Time

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Abstract

Measuring and tracking how individuals become aware of their own understanding (metacognition) cannot easily be measured by traditional tests or assessments. Consequently, this paper presents the development and application of a rubric to examine qualitative data that illustrates how graduate students in science education, who were enrolled in a Design, Engineering and Technology (DET) course, became aware of the changes in their understanding of DET. Weekly reflection papers, weekly written pre and post tests and lesson plans were used as data sources. A rubric linking the course outcomes with six major categories (engineering as a design process, gender and diversity, societal relevance of engineering, technical self-efficacy, tinkering self-efficacy and transfer to classroom teaching) was developed to code text. Several passes through the data led to the refinements for the six categories that allowed the coding of almost all of the text. We specifically looked for shifts in understanding over a 15-week period and an awareness that these shifts were taking place (e.g. “It’s not that I had a bad attitude about technology to begin with, rather this class as a whole and our group project has forced me to think about its appropriate applications at the K-12 level.” and “Both technology education papers addressed the difference between technology education and educational technology – two different concepts I had not thought of before”). Our technique allowed us to capture the subtleties of understanding and the progression of metacognition. The rubric demonstrated that the DET course had a strong impact on students thinking about and applying DET to teaching.

Introduction

Quantitative approaches to assessment can tell you how much, how many or whether group A outperforms group B and provide descriptive statistics for a data set. However, quantitative analysis is unable to tell us why a group of students did well or poorly on an assessment. And, although quantitative techniques can be applied to data sets that are products or artifacts (e.g. a robot designed to perform specific tasks) qualitative techniques provide additional descriptive information as to the quality of the performance. Furthermore qualitative techniques, when used to evaluate large amounts of complex written materials, provide the flavor of the data by identifying salient quotations to support conclusions. Qualitative data, once analyzed with a rubric, can be reduced to numbers by assigning a numerical value to particular types of responses. However, doing so reduces the information available to a researcher.
Many people prefer quantitative approaches to assessment because they are perceived as more rigorous than qualitative approaches. A t-test for differences between two means tells you whether or not groups are statistically significantly different. There is a sense of confidence in numbers based on the belief that numbers are objective and scientific, which, in turn, implies that they are accurate and meaningful. This sense of confidence can be misplaced in light of what we know about test bias, current thinking about the purposes of assessment, and measurement error. Rather than ranking or selection based on test scores, assessment now emphasizes understanding thinking, as well as the nature, consistency, and quality of performance in a variety of contexts. The move toward new ways of assessing (e.g. performance, authentic, portfolio) necessitate new ways of judging performance that rely more on qualitative than quantitative techniques.

The National Research Council, operating agency of both the National Academy of Science and the National Academy of Engineering, supports new approaches to assessment and greater use of qualitative data. In Classroom Assessment and the National Science Education Standards, the Council recommends less emphasis on “Assessing what is easily measured, Assessing discrete knowledge” and more emphasis on “Assessing rich, well-structured knowledge, Assessing scientific understanding and reasoning”. The former quote describes data that is amenable to quantitative analysis and the latter quote describes data amenable to qualitative analysis.

To overcome the perceived lack of objectivity and rigor of qualitative assessment, scoring rubrics should be developed. By a scoring rubric we mean a set of guidelines (categories) that can be used to identify or make judgments about the meaning or quality of text, an utterance, or artifact. When creating a rubric one must ensure both reliability and validity.

Reliability refers to the consistency of the judgments. To have reliability, the rubric should enable two or more individuals scoring the same qualitative data to arrive at the same judgment or for one individual scoring similar data at different points in time to reach the same conclusion. Validity means that the rubric assesses what you intend it to measure. Validity comes in many forms such as construct or face validity and often require cross-validation (e.g. correlating your measures with others claiming to measure the same thing or asking students if coded statements represent the way they would talk about what they learned). And, while rubrics can not account for all of the characteristics of every piece of data, the ability of a rubric to capture general, synthesized criteria is enhanced by going through an iterative process to refine the categories.

The process used to refine categories of a rubric consists of discussions, negotiations, and adjustments that arise from 1) clarifying the purposes, goals and objectives to be assessed; 2) reconciling differences in judgments as scorers use the rubric; and 3) examining the amount of data that can be scored with the rubric to insure that the maximum amount can be coded.

**Purpose**

The first purpose of this paper is to describe how a rubric was developed to assess the impact of a course in Design, Engineering and Technology on students’ understanding of; 1) engineering as a design process, 2) issues of gender and diversity in relation to DET, and 3) the societal relevance of engineering to students’ everyday lives. We were also interested in determining the impact of the course on; 4) students’ technical self-efficacy, 5) tinkering self-efficacy, and 6)
their ability to transfer their knowledge of DET to classroom teaching. The second purpose of this paper is to demonstrate, by applying the rubric to our data sources, that the DET course had an educationally significant impact on students in each of the six categories listed above.

**Context of the Study**

The study took place in the context of a graduate course in science education. The development of the course was supported by a Bridging Engineering and Education grant from NSF. The grant was written and the course created and taught by a team of faculty from the College of Education and the School of Engineering. The course was a pilot, based on a broad survey of DET needs of K-12 teachers, to determine how to infuse DET concepts into undergraduate teacher education and the preparation of graduate students who would become science teacher educators in Colleges of Education. We also wished to determine the impact of the course on the participants.

Nine graduate students agreed to participate in the course and be studied. All were in either a science education masters or doctoral program and had good undergraduate backgrounds in science or engineering. The course was taught by two engineering professors and one professor of science education. An educational psychology professor and a graduate student in science education participated in the evaluation. The class met in an industrial engineering lab with access to a wide range of materials, tools, and technical assistance. The class was held weekly for 3 hours but frequently ran overtime due to student interest and engagement. Students were required to read assignments from both the science education and engineering literature. Students were pre and post tested each week on the readings. Students wrote weekly reflections that addressed the readings, class activities, what they were learning, and personal insights. At the beginning of each class readings were discussed and students shared their reflections. In total, each student produced 40 individual pieces of text of varying length (reflections, pre and post tests) that became the data for this study. Students worked in teams writing lesson plans to use DET in K-16 classrooms and followed the steps in the design process, to create a functioning prototype of an artifact. Lesson plans and creation of the artifacts were not used in this study. However, reflections often contained references to the projects and lesson plans.

**Development of the Rubric**

To analyze the qualitative data, a rubric needed to be developed. Construction started with a meeting where each researcher generated categories they considered to be the most important course outcomes. The categories were discussed and refined to a final list of six main categories. These were an understanding of the engineering design process, issues of gender and diversity in relation to DET, the societal relevance of engineering to students’ everyday lives, as well as changes in students’ technical self and tinkering self efficacy, and students’ ability to transfer their knowledge of DET to the classroom. In addition, subcategories under each main category were generated, discussed, and a total of 44 were agreed upon.

Next, we generated a list of the topics that what would constitute evidence for how the students enrolled in the DET course were meeting the expected outcomes as defined by the six categories of the rubric. The examples of evidence were discussed, added to and eliminated until all researchers come to a consensus. The next to last step was to pilot test the rubric with data. In
order to examine how well the rubric captured the data, we selected two students for preliminary evaluation. One of the selected students was a male and the other one was a female. We analyzed their data using the scoring rubric. As a result of this evaluation, we added two subcategories under the transfer to the classroom category, *engineering as a career* and *critical perspectives*. The final rubric included 46 specific categories for the six categories (Figure 1).

![Figure 1: Rubric for DET course](image)

Each student was given a pseudonym and then the data was coded by determining which of the categories of the rubric best described the piece of text. For example a piece of a students’ text might be labeled as best fitting in the category of *Gender and Diversity* and that the text was also an example of a student talking about shifts in their own behavior vis a vis gender issues. We also looked for metacognitive processes (thinking about one’s own thought and understanding) in students’ writing that included students’ thoughts about their own learning, changes in understanding and other types of insights gained through reflection and writing. Because it was used in this way, the rubric was not a checklist to determine if a category was present or absent.

All of the text was coded by one researcher and then by a second researcher. Differences in coding were reconciled through discussion. Then, the second researcher identified the trends in the data coded for each category and developed the assertions e.g. students were surprised that they held misconceptions about technology - thinking of technology as only limited to computers. The final step was to select the examples that supported (warranted) the assertions.
The Engineering Design Process: The intent of this category was to determine how students understood and thought about building an artifact; acquired vocabulary; understanding concepts; using tools such as process, analytical (modeling), experimental, technology, and communication; engaging in collaboration; and making connections to science and to the assigned readings and research. For example, this piece of text by Amy was coded as understanding most of the steps in the design process, a shift in understanding and metacognition - “I thought design was another word for drawing, and since then have learned that drawing is a part of the process, designing incorporates a thought process, a problem solving process, modeling and then presenting.”

Gender and Diversity: The intent of this category was to determine whether students were aware of issues related to women’s participation in engineering and the low number of under-represented minorities in engineering and whether these issues were being examined critically from multiple perspectives. This text written by Eric was categorized as an example that illustrates his awareness of how gender influences how students work in groups, as well as concerns about his own teaching - “So how to address these issues, not only in my classroom as a teacher, but also in my classroom as a student? These are not just theoretical questions; I would like to find strategies that will work in my current situation. In the next few labs, I plan to experiment with approaches to 1) encourage the female students in my group to take a firmer lead in our investigations, and 2) find a way to diminish the perception that I am the sole “tool expert” in the group.”

Societal Relevance of Engineering: The intent of this category was used to determine whether students had become aware of the role of engineering in everyday life, and whether students did or planned to apply DET concepts in their teaching. The following text, written by Isabel is an example of her perspective of the societal relevance of engineering– “Promoting design projects in the classroom helps students prepare for the real world.”

Technical Self Efficacy and Tinkering Self Efficacy: The intent of these related categories was to determine the effect of the course on self-efficacy. We were trying to capture shifts in negative to positive talk (a critical component of self-efficacy) and comments on competency. We looked for statements referring to the ability to be successful or actual success in an activity that was perceived to be highly technical (e.g. programming) or required skills such as soldering or wiring. Beth’s response is a good example of a comment on competency - “I am confident with tinkering. I notice that my confidence level increases when there is less at stake.”

The sixth category, Transfer to the Classroom, was created to capture how students thought about DET in the classroom and how well they were able to transfer their understanding to the K-16 classrooms they were teaching in or had taught in before. We looked for the transformation of what had been presented to students and their own understanding of DET into a form that was understandable to younger learners, learners with poor science backgrounds, or learners with misconceptions about design, engineering, and technology within the context of the existing curriculum. George’s thoughts on this topic are a good example of several aspects of integration –“collaborative problem-solving project (environmental clean-up of leaking gasoline) exemplifies the use of different groups of students (algebra, geology, and technology) to combine their efforts and solve a problem. My question is: Why not make technology literacy a part of all courses (particularly in math and sciences) so all of the students could understand the
process and participate in each of the processes”. Furthermore, if technology literacy is embedded in science and math curriculum, even as budget cuts are made and courses eliminated (which is happening to technology courses and technology staff in Arizona school districts today), opportunities for students to acquire technology procedural and declarative knowledge will remain.

**Results**

Following the cannons of qualitative research, we will first provide a synthesis of the findings and then provide one or more selected supporting quotations that are exemplars of the larger data set. We will not attempt to provide quotations for each of the 46 subcategories of the rubric. To maintain confidentiality, actual student names are replaced by pseudonyms.

The analysis of data related to the *Engineering Design Process* indicated that the students: recognized the differences (as well as similarities) between science and technology; developed an understanding of the design process; developed a vocabulary (e.g. sensors, actuators, microprocessors) based partly on experiences with hands-on activities; and discovered the importance of team work in the design process and problem solving. They also uncovered their own misconceptions about design and modeling, particularly as a result of the hands-on activities and group projects.

David: “Our group learned an important lesson last week. Our original design for our project was going to transmit location, direction, speed, identification and whether or not the device had crashed or not. After speaking with an advisor about the chip and feasibility of our design, we found that this was nearly impossible within our time and funding constraints. Much like the problem with concept designs, this has given us a glimpse and new respect into the world in which engineers live. I had never realized how nearly impossible a project can be, yet in the beginning it seemed so simple. We had this dreamy view like we would simply slap this here, rewire this there, reprogram that there and whala, done. Even with a concept design as simple as ours, just getting the sensor to read and display location is nearly impossible. Thus our project has been whittled down to merely displaying location. This, as Steve has so politically called it, a "proof of concept". The point being that if we can display location, taking the derivative of this we can find speed as our next step. Simply adding on pressure sensors and relaying the vehicles description is a simple task. Getting the sensor to display position is crucial to the project.”

The data also indicated a shift in understanding of the design processes that emerged toward the end of the semester. Below is a student’s answer to the question, *Describe the design process, as you understand it*, as she wrote it at the beginning and at the end of the semester.


Isabel: “The design process involves a combination of technical expertise, team-building skills and creative thinking. It is more than just putting an idea on paper and building it. Like research, you have to find reasons why your idea won't work (disconfirming evidence) and try to come up
with other plausible solutions. It is only when those alternative ideas are exhausted and you still think you have a good idea can you proceed with creating an artifact from this idea.” (5/5/2003)

The analysis of Gender and Diversity issues revealed that the students realized how technical problem solving can provide learning opportunities for all. This led to an understanding of the importance of gender diversity in the design process so that the students were able to see how DET could support diversity. They also recognized the gendered nature of their own interactions with their peers as they developed their group projects and created lesson plans. Both male and female students commented on the gender differences they saw in their own group interactions.

Isabel: “In our group for example, the two males are definitely more excited about what the tools actually do, where the females tend to be more focused on accomplishing the task at hand. While the females may not necessarily surrender their own ideas to those of the experienced physicist, we are not as interested in trying other unrelated, yet “cool” tasks the tools may perform.”

David: “Being reminded of our roles would help some. From taking many of Dale's classes [in gender equity] I'm a lot more conscious of my role in learning and teaching situations. I still need work though. I still need to video tape myself and watch my interactions with my students. Should we start assigning roles? Should we tell someone, this is the way you will react in this group today? Is this a good thing for learners to do is have a permanent role in a group? I truly wonder about this.”

Amy who was teaching at a middle school wrote about how design projects can be used to promote diversity the classroom.

Amy: (referring to her own classroom) “… on some level I have found these “projects” to be an equalizer in my class. The students that have excelled in this section were students that you wouldn’t expect. Girls, special needs, English limited students and low academic students. They have a natural curiosity of the world which falls nicely into the definition of technology and its components.”

The Societal Relevance of Engineering category indicated that students found ways to integrate history of technology with social studies in the classroom, and they realized the importance of technological literacy in everyday life.

Isabel: “First, the goal of technological literacy for all. I agree with this idea because like many science educators who would argue the same for science literacy, we need to be able to make informed decisions concerning the environment, ethics and politics. Oftentimes we can be easily swayed to jump on a popular bandwagon, such as getting a smallpox vaccine, without knowing what questions to ask.”

As a result of applying the Technical and Tinkering Self-Efficacy categories to the data, we found that students recognized more situations where they tinker in their everyday life than they had at first thought. In addition, females recognized the changes in their tinkering self-efficacy and technical self-efficacy depending upon the nature of the situations. Females felt more confident when there was nothing at stake. Below are responses to the question, Honestly describe your
tinkering self-confidence. Note that there is a positive change in all the responses from the beginning to the end of the semester but that the females still qualify their answer.

Beth: “My tinkering self-confidence all depends on the value of the object that I am tinkering with. If it is expensive or a hard to find object, I am much more cautious with tinkering. But, if it is cheap and easily replaced I am very confident with tinkering.” (1/27/2003)

Cybelline: My tinkering self-confidence is very good, if I know the area. For example I know a lot about biology, but I don't have the [background of] engineering, so I need the meaning of terms about engineering. (1/27/2003)

Cybelline: I did it without having engineering background. We should work step by step to understand each item, where it works. I think I combined my scientific background with new knowledge. (5/5/2003)

EJ: If there is a good mentor to show me an example, I can do it, but with the manual [tasks] I am a slow learner. (1/27/2003)

EJ: Although the sensors, motors were quite interesting, I felt I had to be exposed to materials or parts of the mechanical things more. When I saw the other groups working, I thought "I did not have basic skills like them." So, I sometimes felt myself not prepared. However, my fear of tinkering some mechanical or technological improved positively in daily life. (5/5/2003)

The female’s responses are in sharp contrast to what are typical male responses at the beginning of the semester.

George: I love ripping apart stuff. I give myself a 10/10 on this. I give myself an 8/10 on putting it back together. The amount of parts left over is directly proportional to how badly it works after I get hold of it. (5/5/2003)

Eric: Very confident. I've taken apart many things just to see how they work. Very confident. Have built computers from scratch and am an experienced programmer as well. (5/5/2003)

An analysis of the students’ ability to Transfer to the Classroom indicated that the graduate students became aware of their own, their students’ and others’ misconceptions about technology and modeling. They also became aware that they had been using DET in the classroom without knowing it, and they became critical about the implications of technology in schools and the financial limitations of ever changing technology.

Isabel: “I have to admit that I am one of the many people the article describes as having typical ideas of technology education. In my experiences in school and the workplace, the technology teacher, department or support line were all directly and solely related to computers. In fact, the tech department would be housed off site at the district building and the technology chair had her own office at district.”
They were also able to make connections and integrate science and technology as well as reflect on their own teaching in light of what they had been reading and doing. George puts all of the pieces together.

George: “The Carter et al. Paper makes good sense to me. If the objectives of a lesson is for students to learn a conceptual system (circuits), and tools are being utilized by the students to construct the procedural and declarative knowledge, then students need to be: proficient in using the tools, have the opportunity to explore through gender and culturally unbiased activities, and give students the freedom to generate hypotheses, design tests for the hypotheses, perform and analyze the tests, and come to conclusions. Furthermore, the activity is more cognitively stimulating for students if they construct the knowledge in teams and justify to each other their actions and thoughts. If on the other hand, the objective of the lesson is to have students become proficient with tools needed for exploration, students need a differently crafted activity that includes: proper modeling by the instructor of the proper use of the tool, opportunities for students to practice and use applications (that interest them), correction of student procedures, and plenty of practice and transfer activities with the tools. A focus on engineering design appears to be as a reflective practice, experiential, problem-solving. This parallels effective science education.”

Even Frank, the student who struggled most with the ideas presented in the class and was reluctant to put his thoughts in writing began to think about his own teaching as a physics instructor. Notice how he starts off wanting to maintain the separation between science and technology but then begins to think about how the two can become complimentary; perhaps even taught together.

Frank: One solution to all this is to develop a separate technology class. While this will no doubt be an asset to those who aspire to be an engineer, this will be limited to this population of students. Perhaps a more practical solution would be to change the teaching of science to compliment technology education. Science and technology are separate but not completely independent of each other. Science gives an added knowledge base that technology can be built upon. And technology aids science in its work. Furthermore, the scientific method closely parallels the design process of the engineer. So if the science classroom is used to instruct students in the scientific method (by practice) then learning the design process can then be taught by comparison. Students can learn to solve a given problem by projects which put students in a position where they can develop problem solving skills. Science education can also play an important part in this by making connections between the science being learned and the applications of technology which are its use.

In addition, two students developed a critical perspective about their own undergraduate engineering and on the job education. A student defined the DET course as a bridge connecting theory and application.

Eric: “This bridges the gap between theory and application and allows students the opportunity to gain a better deeper understanding of the science and engineering concepts. This is definitely something that I missed out on in my science and engineering education.”
Beth: “Although, I worked as an engineer I was not trained or educated as an engineer. I was never formally exposed to the design process. I learned it by using it on the job, on the job training.”

Conclusions and Discussion

The rubric we developed proved very useful in analyzing a large complex data set. Furthermore, it provided us with a way to clarify what we felt was most important for students to learn about DET and then to determine whether or not they had learned the concepts. The information we obtained from the pre and post tests, weekly reflections and the project will help us develop future DET courses for the teacher education and the science education graduate program. In particular, we will spend more time with activities designed to improve the tinkering and technical self-efficacy of female students. We will also have to devise additional ways to get at the thought processes of the male students. In comparison to the females, they wrote less and were less inclined to be self-reflective.

In addition, we will create a rubric for future course development before we outline the course. The a posteriori process we engaged in to develop the rubric for this study helped us identify tacit assumptions that were not shared among all of the instructors and forced us to focus on what was central and what was peripheral to student learning. We recommend anyone considering new course development or revisions of courses to first clearly identify the goals and objectives the course and then to identify what would constitute evidence for meeting those goals and objectives. This process will move assessment from an emphasis on “Assessing what is easily measured, Assessing discrete knowledge” to an emphasis on “Assessing rich well-structured knowledge, Assessing scientific understanding and reasoning”.

The students who participated in this pilot DET course all had solid backgrounds in science and two had a background in engineering. Yet, they began the course with misconceptions about DET. They were quick to catch on and made good progress in translating what they were learning to the K-16 classroom. However, we wonder if students with poorer backgrounds (e.g. undergraduate elementary teacher education majors), the target of our next DET course, will have even more misconception or perhaps even no conceptions at all and what we can do about these misconceptions. We expect that it will be more difficult for undergraduate elementary teacher education majors to transfer what they will be learning in their DET course to classroom teaching, both because they are novice teachers and because their grasp of science is poorer.

On the other hand, it was clear from our data that the graduate students with good science backgrounds learned about DET by doing DET. Even the two engineering-background students increased their knowledge of DET and of the relationship of science and technology from the hands-on activities. This is an instruction approach that we advocate in teacher education and will model with the undergraduate elementary teacher education majors in the hope that they will teach as they have been taught. We recommend that more time be spent in doing design and less time listening to lectures in order to develop a deeply embedded understanding of DET, rather than DET as a series of steps.
Furthermore, we believe that we have shown that using a rubric, to determine students’ understanding, is the best way to evaluate the multifaceted training that students receive in engineering to work in business and industry, where they must understand the societal relevance of engineering and must become aware of gender and diversity issues in engineering. We encourage engineering educators to consider using more qualitative data to explore student understanding by using the development of rubrics to structure the creation of courses to help further reform in engineering education.

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References


Biographies

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