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Student Reflection, Self-Assessment and Categorization of Errors on Exam Questions as a Tool to Guide Self-Repair and Profile Student Strengths and Weaknesses in a Course

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Introduction

One significant challenge in higher education involves working with students to repair gaps in their knowledge and understanding. Scores of student work products (assignments, exams, essays, oral presentations) are often used as indicators of student performance and to determine whether or not students have mastered the learning outcomes of a course and are ready for the next course in a course sequence in a discipline. However, using these positive indicators is often not sufficient to gain a detailed understanding of the level of students' mastery and preparedness for each specific concept, which may be imperative for future courses in the discipline and which is essential in their building a professional identity within a discipline. Persistent student errors in various categories[1], while not enough to prevent the student from passing a class and moving forward, can often create lasting academic and professional challenges for students. An understanding of gaps in students' preparedness for future course in the discipline can be gained through student reflection, self-assessment and categorization of errors on exam questions.

Self-assessment involves asking questions such as "How am I doing?" and it is an act of judging oneself and making decisions about the next step[4]. Student self-assessment has been shown to play an important role in leading to stronger student motivation, better learning, and higher achievement[2,3]. It has been considered one of the most important skills for students' lifelong learning and future development[4-8]. Researchers have suggested that students should be actively involved in the process of providing feedback and that feedback given to students must be interpreted by students themselves and internalized before it can impact on students' learning and further study[9-11]. Guided reflective thinking can often be used to guide students through self-assessment activities. Guided reflective thinking is a systematic way of thinking about one's actions and responses such that future actions and responses can be improved[12]. Dewey[13] describes a reflective operation as having two essential elements "(a) a state of perplexity, hesitation, doubt; and (b) an act of search or investigation directed toward bringing to light further facts ….". Other established approaches for promoting reflective thinking include prompting students with questions and worksheets to identify and clarify problems, providing space for students to journal their understanding and show awareness or relations and connections or to provide student opportunities to choose and implement alternatives. In the Spring and Fall semesters of 2014, a series of guided reflective thinking and self-assessment exercises were introduced in two core Mechanical Engineering courses as a way to provide students with an opportunity to review their performance and self-assess the 'causes' of a mistake or error on an exam question in order to guide and incentivize self-repair of knowledge gaps. The faculty member identifies the student work as being in error and prompts the student to look not just for the right answer but to investigate and compare their efforts with a standard – looking for reasons and rationales for their actions.

For this guided reflective thinking and self-assessment exercise, students enrolled in two core Mechanical Engineering courses, "Introduction to Engineering" and "Solid Mechanics", performed an exam reflection and self-assessment after each exam/quiz in which they reviewed their performance on each problem and described the actions they would take to improve their performance in the future (i.e. repair knowledge gaps or change study/test taking behaviors). As a further step, students also categorized types of errors made on each concept into the following pre-defined categories: Mathematical Component; Problem Solving Component and Engineering Component. These categories were devised through discussions with other knowledgeable faculty, based on their observations in teaching, and prior research done on error categorization[1]. The purpose of these categories is to narrow discussion on the source or sources (since multiple entries are allowed) of student errors on a given exam problem. Instructions to the student and a description of the categories and divisions are found in Appendix A.

In each of these categories students would compare their solution to a sample correct solution or to lecture notes on the topic and then they would identify all of the factors that they felt influenced their answer. For example, in the Mathematical Component, common error causes were listed as minor mathematics or 'slip' types of errors, Algebra and Calculus errors (mechanics of the process), and errors in understanding underlying mathematics concept. As such each error type would be indicative of a unique repair path for the student for future problems. For example, 'slip' type errors can be addressed by vigilance or changes in behavior while Calculus or Algebra errors may require some re-instruction and practice. The second pre-defined category is the Problem Solving Component, which includes sub-categories related to problem solving techniques, for example, no error, if the error or mistake is not related to problem solving; units mismatch, if the error involves wrong units or a unit conversion problem; omitted part of the question, if students overlooked a part of the problem or was not able to identify what they were solving for; unorganized approach, if parts of the solution were not clearly connected to each other. In the Problem Solving Component, the selections are based on faculty experience with common errors. The third category, the Engineering Component, deals with the engineering concepts and principles and the sub-categories are aligned with Bloom's Taxonomy of educational objectives[14]. These sub-categories are: no error, if the error made on the exam problem is not related to the underlying engineering concepts; knowledge error, if the error is due to inability to recall a definition or property; understanding, if there is lack of comprehension of an engineering concept of principle; synthesis, if students failed to connect parts of the problem and see how they fit together; evaluation, if students interpreted information incorrectly; something else, if the error does not fit in any of the other sub-categories; unknown, if students cannot identify the type of error made.

Upon completion of the self-survey, students' reflection and self-report of error types were collected, and in some circumstances, reviewed by instructors and compared with their answers on the exams. As an assignment, students also analyzed the root cause of the errors for each problem and developed strategies to improve performance in future tests. Aggregate data was also compiled for instructor use to profile the types of errors present in the cohort and to track changes and improvement in error types on subsequent exams. This self-reflection and error analysis serve three main purposes for a course: determination of weaknesses by students used to develop strategies to improve performance on future tests; identification of gaps in students' understanding of the key concepts by faculty members; and reporting to other faculty members on the strengths and weaknesses of a cohort of students.

The guided reflection exercise was deployed for the first time in two different classes to explore two different strategies for incentivizing the activity and to explore the role that reflective thinking can play in an Engineering course. In the Introduction to Engineering course the students were asked to complete the guided reflection exercise after each of the five quizzes. The guided reflection exercise was treated as homework and graded on completion. In the Solid Mechanics course, the guided reflection exercise was presented as an optional activity with the quality of the reflection and self-assessment playing a role in the value applied towards the exam score.

Tool Description and Implementation (Introduction to Engineering)

Introduction to Engineering is a 3-credit core course required for all Engineering majors and was offered to over 1,000 students in over 30 separate sections during the Fall 2014 semester. As an Introduction to Engineering, this course provides a general foundation for the study of engineering and serves as a first exposure to the Engineering design process. While this course focuses on aspects of the Engineering design process, such as decision matrices and project management, the course also introduces limited Physics and Mathematics content in service of the given design project for the term. As a General Engineering course, students in a given section will have a number of different declared majors and, while the class is considered introductory and most of the students are considered “Freshmen”, there are generally a number of students in each section who have upper-level standing. Table 1 shows the learning outcomes of this course.

Table 1. Learning Outcomes of Introduction to Engineering

Course Core Outcome.
1. Understand and practice using the engineering design process; 2. Become familiar with tools, software, and terminology used in engineering; 3. Learn to use engineering models, physical principles, measurements and data to solve problems; 4. Gain the ability to work effectively in teams and recognize the importance of teamwork; 5. Gain basic skills in technical communication (oral presentations, technical reports, presentation of data); 6. Gain experience using basic project management techniques (scheduling, budgeting) to complete projects successfully; and 7. Use creativity to solve an engineering problem related to challenges facing our world.

During the Fall 2014 the guided reflective thinking worksheet was introduced to a single section of the course with 40 students from Mechanical Engineering, Chemical Engineering, Aerospace Engineering and Electrical Engineering. In this section, thirty-seven (37) of the students were Freshmen while three students were Sophomores and one student had Junior-level standing. This distribution is significant because some of the subject matter covered in Introduction to Engineering is introduced before it is covered in other typical first-year engineering courses (like Physics II). Examples of the Physics content introduced during the Fall 2014 section to support the design project included: work and energy; basic electrostatics; batteries and motors; series and parallel circuits; and gears and pulleys. A survey of the Freshmen students in this course indicated that the majority of the students had either Calculus-based or Algebra-based Physics in high school, but around 10% of the students indicated that they had no prior exposure to Physics in high school. In terms of the mathematics level for these students, roughly half of the students were in Calculus with the remainder split between Pre-Calculus and Calculus II or III (Table 2).

Table 2. Mathematics and Physics Survey Results for Introduction to Engineering

High School Physics Level		**Current Mathematics Enrollment**	
No High School Physics	5	Pre-Algebra	1
Algebra-Based Physics	22	Pre-Calculus	10
Calculus-Based Physics	11	Calculus I for Engineers	15
		Calculus II for Engineers	5
		Calculus III for Engineers	6

The course consists of a 50-minute lecture section and a 3-hour laboratory section each week. The first half of the semester is focused on content and skill development and the second half is almost exclusively focused on the design project. The lecture periods are typically used to introduce content while the laboratory sections are used for problem-based learning activities and for student teams to complete the design project. In this course, five (5) quizzes are given to assess student understanding of the key Physics and Engineering Design content while the rest of the assignments focus on the design process or are related to the laboratory activities and notebook.

In previous semesters, after each quiz was given students were asked to review their responses and make improvements to their understanding. Content relating to the quiz material was often reviewed, but no requirements were put on the students to revise and improve their understanding. During the Fall 2014 semester, students were required to complete the exam reflection assignment immediately after each of the graded quizzes was returned. Students were asked to carefully review their solutions, compare their solutions to the sample solutions provided, and answer the following three reflection questions for each exam problem if their original work was not perfect.

- How is my solution different from the solution provided?
- What went wrong with my solution?
- How can I use this information (i.e., what strategy can I use) to improve my performance on a similar problem in the future?

In addition to responding to the three guided reflection questions, students were also asked to categorize the types of each mistake or error made on each exam problem based on the set of pre-defined categories. As described previously, within each category there are several letter coded sub-categories provided with brief explanations or scenarios for students to develop connections with their own errors (see Appendix A for the assignment instructions provided to students).

Tool Description and Implementation (Solid Mechanics)

Solid Mechanics is a 3-credit core course required for Mechanical Engineering majors and was offered to 172 students in two separate sections during the Spring 2014 semester. This course introduces equilibrium, the method of sections, the concepts of stress, strain, mechanical properties of materials, stress-strain-temperature relations, and applications to force transformation and deformation in axial, torsional, and bending of bars. Table 3 shows the learning outcomes of this course.

Table 3. Learning Outcomes of Solid Mechanics

Course Core Outcome.
1. Students will understand the definitions of stress and strain, and basic mechanical properties of materials such as elasticity, yielding stress, Young's modulus and Poisson's ratio
2. Students will apply concepts of strain and stress to the analysis of statically-determinate (a) and indeterminate (b) bars under axial loading
3. Students will apply concepts of strain and stress to the analysis of statically-determinate (a) and indeterminate (b) shafts in torsion
4. Students will analyze the shear, moment distribution, and calculate stress in beams under bending
5. Students will predict deflection in beams under bending, and analyze statically indeterminate beams

The course provides a foundation to a series of required courses in the discipline: Structural Mechanics; Principles of Mechanical Design; Finite Element Analysis; Mechanical Engineering Design I & II. In this course, homework Assignments, three preliminary exams, and a final exam are used to assess the learning outcomes. Students have to earn a letter grade of C or above (above or equal to 70%) to move forward in this series of courses.

In the past, after each of the preliminary exams was given, graded work was returned to students within a week for timely feedback. Exam problems were reviewed and common mistakes and errors were discussed during the lectures. However, repeated mistakes or errors were often seen in following exams and those who received satisfactory grades may have made a mistake due to a serious conceptual misunderstanding which could prevent them from being successful in future course in the series of the discipline. During the Spring 2014 semester, in one of the sections of this course offered to 73 students, an optional exam reflection assignment was given to students immediately after each of the graded preliminary exams was returned. Based on the quality of the reflection and self-assessment, each student who submitted the assignment was awarded up to 10 points (about 6%) back on the exam. Students were asked to carefully review their solutions, compare their solutions to the sample solutions provided, and answer the following three reflection questions for each exam problem, if not perfect.

- How is my solution different from the solution provided?
- What went wrong with my solution?
- How can I use this information (i.e., what strategy can I use) to improve my performance on a similar problem in the future?

In addition to responding to the three guided reflection questions, students were also asked to categorize the types of each mistake or error made on each exam problem based on a set of pre-defined categories for preliminary exams II and III. Submitted exam reflection responses were reviewed by the instructor to confirm the categorization of error types and assign appropriate points based on the quality of the reflection.

Results and Discussions

In the Introduction to Engineering course students responded to the error categorization with a strong effort, but rather low quality. For this exploration of the guided reflection exercise, four quiz questions were examined. These questions included two simple series/parallel circuit calculations; the construction of a torque-speed curve for a linear DC motor and a problem involving gear ratios. Comparison and validation of student self-assessment of error was very difficult to accomplish on the two quizzes. While these quizzes consisted of staged questions on series and parallel circuits and motors, student work on the quiz sheets was often cursory and relied heavily on equations. In some cases it was easy to determine that a student used, for example, the total resistance of the series circuit to calculate the power used by a single resistor, as evidenced by the terms used in their calculations. In other cases, however, student work was almost indecipherable and the faculty member had to rely upon the student's written reflections to determine where the student went wrong.

As mentioned previously, the nature of this course means that students are often introduced to Physics concepts in a limited and focused manner to serve the design project for the term. While the majority of these students were exposed to Physics in high school, and a large number had a calculus-based version, the scores they received and the types of errors the identified indicate that a considerable portion of the class did not have the content properly seated even after the lecture period. Table 4 lists results from student self-classification of errors on a simple series and parallel circuits problem which would typically be covered as a central part of a high school Physics course. (Appendix A contains the codes for the error types). The problem is often an issue of conceptual understanding (category L or K) since the errors students make are often the result of blindly applying formulas without identifying which components are included and which do not apply. Students who made units conversion errors or other simple math errors were quick to identify their mistakes and develop cursory plans for remediating. Students, however, who marked categories N (Evaluation error) and P (unknown) struggled immensely with the content and had little in the way of a self-remediation plan.

Table 4: Student Self-Reported Errors on Series and Parallel Circuits Quiz Problems

	Circuits Problem 1	Circuits Problem 2
	Problem 1	Problem 2
Total Students	32	32
Students Reporting (A)	17	25
Students Reporting (B)	7	2
Students Reporting (C)	4	2
Students Reporting (D)	6	3
Students Reporting (E)	17	23
Students Reporting (F)	9	1
Students Reporting (G)	3	4
Students Reporting (H)	4	4
Students Reporting (J)	12	20
Students Reporting (K)	8	4
Students Reporting (L)	10	4
Students Reporting (M)	0	1
Students Reporting (N)	5	2
Students Reporting (O)	0	1
Students Reporting (P)	0	2

On the gears and motors quiz the majority of the students identified their errors as relating to serious gaps in their understanding of both the mathematics and engineering concepts. Units and simple mathematics errors were dwarfed by their gaps in knowledge of the terms and concepts described in the torque-angular velocity graphs.

One underlying issue that the exam/quiz reflections exposed is the wide range of skills and proficiency with pre-requisite knowledge and skills that are often assumed as second nature at this level of education. Students in this course had issues with content such as the equation for a straight line and the conversion of units from rpm to rad/s. In addition, student reflections often provided only cursory responses to the questions and had a right/wrong-bias or behaviorally focused mindset. For example, in response to a question on calculating the torque-angular speed relation for a linear motor, a considerable number of students remarked that their errors were directly related to their inability to remember a formula from high school mathematics.

"I used the wrong equations for this process because I wasn't sure how to show the equation of a straight line"

"I am now aware that because it is a straight line, the equation to base off of is that of a straight line (y=mx+b)"

With some students, the act of developing strategies for improvement and identifying causes were treated as rote exercises consisting of repeated phrases such as "I need to study the concept more and practice". On occasion, however, student plans for improvement were very insightful and also exposed some underlying strategic learning issues which faculty members might not be aware of without giving the students an assignment for reflection.

> *"I have a theme going … I can do & analyze, but I cannot reproduce. Even in my Chem Lab I have noticed I do the lab while my lab partners tell me the concentrations of what I need to mix. I can talk through what is supposed to happen, but I have never done the math … My <u>Strategy to Improve</u> is to start taking over the math sections more in labs and work through the labs we did in class by myself"*

In the Solid Mechanics course, the greatest challenge was in getting the students who needed to repair their knowledge gaps to participate in the optional exercise and to translate their insight to action for the next exam. Since the exam reflection for preliminary exam I did not include categorization of errors, results from only the last two preliminary exams are presented. For preliminary exam II, 32 (43.8% of the class) students submitted this optional assignment and for preliminary exam III the number was 26 (35.6% of the class). Table 5 and table 6 show the grade distribution of the entire class on both exams prior to the adjustments made as incentive to complete the exam reflections, and the percentage of students who completed the exam reflection in each letter grade range, respectively.

Table 5. Class Grade Distribution of the Exams

	Preliminary Exam II	Preliminary Exam III
Total Number of Students in the Class	73	73
% of A's (between 90 and 100%)	31.5%	20.6%
% of B's (between 80 and 89.9%)	19.2%	34.2%
% of C's (between 70 and 79.9%)	21.9%	24.7%
% of D's (between 60 and 69.9%)	13.7%	8.2%
% of E's (below 60%)	13.7%	12.3%
Mean (out of 100%)	77.46%	78.19%

Table 6. Percentage of Students who Completed the Exam Reflection in each Letter Grade Range

	Preliminary Exam II	Preliminary Exam III
Total Number of Students in the Class	73	73
Total Number of Students who Completed the Exam Reflection	32	26
% of A's that Completed the Exam Reflection	26.09%	16.67%
% of B's that Completed the Exam Reflection	41.19%	41.67%
% of C's that Completed the Exam Reflection	75.01%	49.99%
% of D's that Completed the Exam Reflection	50.02%	20.02%
% of E's that Completed the Exam Reflection	37.50%	9.86%

As expected, very few students who received high marks on their preliminary exams completed the guided reflection exercise. It was surprising that data from this semester also shows that the majority of students who received an E on the exam did not choose to complete the exam reflection, the reason of which is not clear to the authors. However, the individuals that received an E on preliminary exam II and chose to complete this exam reflection assignment all improved their performance to various extents on preliminary exam III (out of these 6 students, 3 received a B on preliminary exam III and the other three also earned more points). Whether this improvement is due to a change in behavior and intent during the exam, as prompted by reflections on the types of errors, or by the guided reflection exercise prompting students to repair gaps in their understanding is a topic for future study.

The three problems which comprised preliminary exam II were used to assess the learning outcomes 1 & 2(a), 3(a), and 2 (b), respectively (see Table 7) and those on preliminary III assessed the learning outcomes 3 (b), 4, 4, respectively. The following table shows the types of errors (refer to Appendix A for the letter-codes) students have made on each problem of both exams based on their reflection and self-assessment reports (students can report multiple types of errors on each exam problem).

Table 7. Types of Errors Students Made on Preliminary Exam II

	Exam II			Exam III		
	Problem 1	Problem 2	Problem 3	Problem 1	Problem 2	Problem 3
Total Students	32			26		

Students Reporting (A)	28	17	15	12	12	19
Students Reporting (B)	3	5	10	10	12	5
Students Reporting (C)	0	4	2	2	1	2
Students Reporting (D)	1	0	5	2	1	0
Students Reporting (E)	14	14	18	11	10	19
Students Reporting (F)	3	2	2	2	6	2
Students Reporting (G)	12	6	12	3	9	4
Students Reporting (H)	3	10	0	2	1	1
Students Reporting (J)	4	8	9	5	8	4
Students Reporting (K)	14	3	7	5	4	6
Students Reporting (L)	13	9	7	9	5	10
Students Reporting (M)	4	9	3	6	2	4
Students Reporting (N)	12	5	1	6	11	3
Students Reporting (O)	1	5	4	3	1	2
Students Reporting (P)	0	2	0	0	0	0

Error types A, B, C and D are related to the Mathematics concepts and skills that are drawn upon to solve the problem. Error type A indicates that the student felt that there were no errors made which were due to their mathematics ability, while error types B, C and D are mathematics errors of increasing severity. Based on this data, it can be seen that majority of students felt that they did not make any mistakes due to mathematical concepts (understanding & applying). One interesting observation is that 5 out of 32 students (15.63%) reported error type D (error in understanding underlying mathematical concepts) for problem 3 on exam II, which, however, did not include any new mathematical concepts from this course. This suggests that at least a small portion of the students did not fully master the concepts from the prerequisite Calculus courses which have negatively affected their performance in this course, even though they have earned enough points to pass those prerequisite courses.

Error types E, F, G and H are associated with Problem Solving methodologies needed to address the problems, with the first type (E) being no error and the remaining codes increasing in severity. In the Problem Solving category, the majority of students reported that they did not have any issues with problem solving techniques. For those that did, they felt they either omitted part of the problem (G) and/or used an unorganized approach (H). While omitting part of the question is easy to fix in future exams, an unorganized approach could be an indicator of a more serious gap in study skills.

In the Engineering Components category, student responses ranged the widest. Error types associated with this category were explicitly drawn from Bloom's Taxonomy in an effort to identify the types of thinking errors involved in these multi-stage and sophisticated exam problems. In this category three issues stood out as most prominent: issues with missing information or incorrect/incomplete understanding of the concepts and issues relating to the interpretation of information or graphs/data, In this last category, students self-identified that they had the process correct, but that their solution was not correct because of a misinterpretation. Students who reported error types K-N showed issues with different levels of mastery of the key concepts. While these students may be able to earn enough points for a letter grade of C for this course, these issues, if not addressed, could seriously hinder their progress in the Structural Mechanics course. This type of feedback is very important to the instructor, who could identify each individual's weaknesses and give individualized suggestions to the students; and provide further instruction to help students master these concepts.

While the data on student errors, their frequency and relationships to their grade/course performance are illuminating and have provided direction for future improvement of the guided reflection exercise, it is the qualitative data obtained by the activity that has provided some of the greatest indications that the reflection process has had a serious positive impact on students. Since students were explicitly asked to reflect on their performance and roots of their issues with the content as well as to record their reflections, this prompted many students to respond to questions about their education with a level of maturity that was unexpected. As such, this reflection, self-assessment, and categorization of error types also provides a great tool to help students take ownership and responsibility of their learning; actively reflect on their study approaches and problem solving techniques; identify weaknesses; determine the root cause of mistakes or errors; and develop strategies for future improvement. For example, a student who did not understand the basic concepts very well and used an unorganized approach for a problem pointed out the following in the reflection report:

"Having a greater understanding of the fundamentals will give me a solid foundation to build off of for future concepts and problems. If I don't understand these basic ideas, I have no chance of recognizing the path to the solution for any other problem besides the specific ones I study. I need to change my study habits and approach the answer by working backwards from what is given."

Although the goal was for students to use this reflection to identify and repair gaps in understanding, the process of reflecting on the skills and content of the course often impacted students of a level much deeper than a given assignment. For example, in a reflection report, one student mentioned that:

"....is because of my misunderstanding of the concepts of strain and deformation. In my understanding, the border between the strain and the deformation was unclear. It caused me to use the value of the deformation as the value of strain and also to have a result that was not concluded. I was supposed to need to find the new diameter of BC, but instead I determined the lateral strain. Through this mistake, I made the border between the strain and the deformation much clear. Strain is a dimensionless quantity, a ratio of change of length to the original length whereas deformation is an actual change of length. Then it makes sense that deformation has units but strain does not have units. It helps me to understand what I am actually doing on the problem instead just to calculate numbers."

Future Work

The guided reflective thinking exercise was introduced in to two different courses to explore its potential for use as a reporting mechanism as well as to inform both student repair and remediation as well as to suggest instructional reform. In this pilot project a number of insights were gained on its use at each level of instruction as well as means by which information can be compiled and shared.

Within the Introduction to Engineering course, one challenge of the guided reflection exercise is to help students see the value of reflection as well as the creation of a smooth and organized system for reporting. Future efforts will scaffold the process of writing reflections, using case studies, and limit the number of problems which the students need to reply: the goal being to model behavior rather than enforce. A worksheet or standard form is also needed to facilitate the process. In this first exploration, students would use almost any available sheet of paper to complete their assessments, which made it very difficult for the faculty member to retain and correlate responses. The reporting system using labeled categories was useful for some errors, but became difficult to manage when the errors involved rather sophisticated: errors in the Evaluation and Synthesis level were difficult to discriminate. A more automated or uniform method for distributing and collecting responses would be desired.

Information gained from the student reflections will be used to on-board new lecturers to the program and as a bulletin to inform current lecturers about the "profile" of the students in the course. In addition to informing faculty on the current state of student understanding with the content, it was fairly clear that the guided reflection exercise also provided significant feedback to the faculty teaching the course. Missing pre-requisite knowledge and well as common troubles with the content indicate that time and effort should be spent revising instructional materials and helping students repair existing gaps.

In the Solid Mechanics course, one of the greatest challenges was implementing the tool in the course. While the addition of categories of errors greatly simplified the reporting process, the effort of reviewing all the reflection reports and compiling the data without the support of a teaching assistant caused a considerable increase in instructor work-load. A web-based tool for self-reporting could be developed to collect, analyze, and display the data in a more effective way. In addition, since one future objective is to provide reports to department chairs and other faculty, such a web-based tool could also be used to generate a report based on the final exam (if used to assess all the course learning outcomes) at the end of the semester, showing the error types and the frequencies for each error type, for each course learning outcome. A report with this information will provide much better and detailed indicators of student performance, as well as their weaknesses, and can be passed to the faculty members teaching the future courses in the discipline. Future work in Solid Mechanics will also focus on methods for increasing participation from students with lower grades and in following up with strategy plans and concept/skill reassessment.

Conclusions

As a first implementation of a guided reflection exercise, a number of useful insights in to student preparedness and effort to self-improve were observed. With the primarily first-year Introduction to Engineering course, the guided reflection activity exposed a number serious gaps in presumed skills and concepts which are considered "staples" for higher education. Student responses on the guided reflection exercises also exposed the challenges students face with classical, and well researched Physics issues such as series and parallel circuits. While students in this introductory class often took the approach of "I'll remember for next time" when writing their reflections rather than developing specific strategies the information gained and the attention paid to repair and remediation, the information gained about their performance added to the continuous improvement methods for the course. The efforts in this class also suggest that within reflective thinking there is a spectrum or range of maturity and response which needs to be nurtured, encouraged and taught.

In the slightly more advanced Solid Mechanics class, the student responses were much more elaborate and it was seen that the guided reflection exercise could be a useful tool in helping struggling students improve and focus. The added an element of quality and an impact or opportunity to impact the grade for the assignment improved student access for the middle functioning students. It is unclear whether the reflection exercise helps students repair their gaps or simply prompts the students to pause and reflect on the possible cause of their error/low performance rather than just simply accept the low grade "move on" to the next exam, but the structures are in place for future re-testing on these questions.

The challenge with this approach is that it requires the instructor to both review the student work on the exam and review and decipher the student reflections. As such, the effort for both student and faculty member was often quite high. Selective application of the tool (even to just one or two problems on an exam or quiz) and a system which rewards depth and quality of thought are indicated for future work.

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Appendix A. Exam Reflection Instructions

Exam Analysis and Reflection

Being able to analyze your exam and reflect on your errors is an essential part of the learning process. For the exam analysis/reflection, please answer the following three questions for *each of the problems* on exam and submit a copy of your exam with the analysis/reflection.

1. How is my solution different from the solution provided?
2. What went wrong with my solution? Please compare your solution to the answer key and analyze what went wrong. Please do **NOT** give equations, or re-write the problem, or re-solve the problem.
3. How can I use this information (i.e., what strategy can I use) to improve my performance on a similar problem in the future?

For each error you discover, please also review each of the following three categories of errors and identify the types of errors you have made. Indicate this by including the letters corresponding to the types of errors (e.g., A, F, G, and J).

For Example:

Problem #3: **A, F, G and J**

"How is my Solution Different" Section

describe how your solution is different from the answer key provided

"What Went Wrong" Section

describe what went wrong in your solution as compared to the answer key (without giving equations or re-writing the problem)

"Strategy to Improve" Section

describe your strategy to improve your work in this area

TYPES OF ERRORS:

1 Mathematics Component

A	No Error	Not a problem for me
B	Minor Mathematics "Slip"	Something I can fix on my own (classic "doh!")
C	Algebra and/or Calculus Errors	My work contains some algebra and/or calculus errors – "I know how to do it but I am having troubles with the process" (I could use some re-instruction and practice)

D	Error in Understanding of Underlying Mathematics Concept	There are gaps in my understanding of a mathematical concept and I don't know how to apply it (time for extra help sessions)

2 Problem Solving Component

E	No Error	Not a problem for me
F	Units Mismatch	The units I have are incorrectly converted (either from one system to another or with a prefix error)
G	Omitted Part of the Question	In reading the problem I over-looked a part of the problem or I did not identify what I was solving for
H	Un-organized Approach	Parts of my problem solving were "all over the place" – thoughts and side work don't connect nicely with the other parts of the problem – it looks messy

3 Engineering Component

J	No Error	Understood all engineering principles in this problem
K	Knowledge	Did not know key definitions or properties (a definition or basic equation I could have looked up if it were an open book exam – but not an example problem)
L	Understanding	There were some core concepts that I did not completely understand and these impacted my ability to solve the problem (if you are very confused about the problem – odds are it is something in this category)
M	Synthesis	Had troubles figuring out how the parts of the problem fit together
N	Evaluation	Interpreted information, data or graph wrong and this influenced my work – but the process was essentially correct
O	Something Else	Made an error but it doesn't match with anything on this list
P	Unknown	Can't quite figure out how I messed up on this problem