Getting the "big picture" in engineering: Using narratives and conceptual maps

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INTRODUCTION

The Picker Engineering Program at Smith College is the first undergraduate program leading to a degree in engineering at a woman's liberal arts college. The foundation and rationale for the program conceives of engineering as connecting basic scientific and mathematical principles in the service of humanity. Thus imagined, engineering finds itself well situated at a liberal arts college. Moreover women have not been adequately represented in the field of engineering and the program at Smith College will help remedy this. The engineering program's goal is to educate engineers who are adaptable to the rapidly changing demands of society; preparing them to lead society toward an equitable and sustainable future.[1] The engineering faculty members realize that establishing this program and achieving these ambitious goals will require substantial innovations in pedagogy and curriculum. This paper describes some of the pedagogical approaches that are being put into place. The creation of this pedagogy is a work in progress.

All the pedagogical innovations share several goals and chief among these is that the learning be meaningful rather than rote. Too often engineering education has been organized around the teaching and learning of procedures to be applied to solving particular classes of problems. The pedagogy practiced in engineering courses typically takes a "bottom-up" approach, adding incremental bits and pieces as students tackle increasingly difficult problems. The hope is that students will eventually get the big picture. The all-too-frequent reality, however, is that students cannot transfer knowledge. This becomes evident when they are unable to solve problems even slightly different from those used for practice and instruction. The lack of transfer is even more apparent across courses. This narrowness of learning and lack of transfer is a widely recognized problem in engineering education and is eloquently expressed by Schneck (2001):

> The exponential surge of material that must now be covered in engineering curricula, its rapid obsolescence, and the general trend toward more holistic attitudes in 21st century education, all require that the engineer of the future be a product of a program of integrated learning – one that teaches students to use unified, deductive approaches to the creative formulation and solution to engineering problems. Moreover, successful engineering programs in the 21st century university will be those that address the current void between product-oriented, skills training, and process-oriented, holistic training. That is, as engineering educators we spend considerable time teaching skills – "how to" techniques for applying the laws of physics; "cook-book" approaches for formulating and

solving specific types of problems; “methods” for integrating, differentiating, using vector and tensor algebra; computer “literacy;” inductive reasoning – and we do so with our own individual bias, our own approach (within the framework of a course syllabus), and our own perception of what we think the student is learning. Rarely, if ever, do we concern ourselves with the process of education, the long-term effectiveness of our efforts… (p. 213)[2]

Much of the literature of cognitive science, particularly as it is applied to instructional psychology agree on the basic requirements for meaningful learning to take place. These are well summarized by Novak (1998)[3]:

1. Relevant prior knowledge: That is, the learner must know some information that relates to the new information to be learned in some nontrivial way.
2. Meaningful material: That is, the knowledge to be learned must be relevant to other knowledge and must contain significant concepts and propositions.
3. The learner must choose to learn meaningfully. That is, the learner must consciously and deliberately choose to relate new knowledge to knowledge the learner already knows in some nontrivial way. (p. 19)

The third of these three requirements focus on what the learner must do in order to learn meaningfully. Clearly, intentionality on the part of the learner is crucial. Even with the best of intentions, learners need to know how to process information in ways that enable them to construct meaningful knowledge. Mayer (2002)[4] describes three processes in which the learner must engage for meaningful learning to take place. They are attend, organize, and integrate. Learners must pay attention to the relevant and important content, they must organize the content in a structure that is faithful to the disciplinary structure of the content, and they must integrate the content into their existing cognitive structure (i.e., knowledge).

Stepping back from this extremely brief overview of meaningful learning, it is evident that the instructional role of the teacher is very important but perhaps more important is the role of the learner. For no matter what the instructor does, if the learner lacks the prior knowledge, the intention, and/or the skills to accomplish meaningful learning; it simply will not take place.

This is not to diminish the challenges of designing effective pedagogical practices. Assessing student’s existing knowledge, providing content of a high level and structured so that it is potentially meaningful, using assessment strategies that hold students accountable for meaningful rather than rote learning, creating a learning community that encourages learners to intend to learn meaningfully, and finally providing skills and tools that will assist learners in structuring and integrating content are all part of the teacher’s responsibilities. The faculty in Smith’s engineering program are working on numerous pedagogical fronts. The aspects of teaching that are highlighted in this paper are those that are aimed at assisting learners assume responsibility for their own learning.

We consider all the learner strategies (in contrast to teacher strategies) to be largely metacognitive in nature. By metacognitive we mean strategies that are eventually initiated by the learner and that are directed at self-monitoring and self-regulation. A metacognitive approach to disciplinary instruction has been demonstrated to result in more permanent restructuring of knowledge, better retention and understanding over time, Blank (2000)[5]. Achieving self-monitoring and self-regulation require not only learner intention but a repertoire of learning skills that appropriately and effectively can be brought to bear in a learning situation. Mayer (2002) identifies two classes of strategies that learners can use to facilitate meaningful learning. One he calls structure strategies. These strategies help learners think about the structure of the content they are learning. By accomplishing this, learners meet one of the conditions of meaningful learning. They acquire an organized and inter-related set of ideas, a set that they can continue to build upon rather than a hodge-podge of unconnected facts and formulae. The second class of strategy Mayer calls generative. Generative strategies help learners link new knowledge with existing knowledge. These strategies focus on productive ways of processing information, ways that involve the sort of intentions and consciousness necessary for meaningful learning.

This paper reports on the use of two strategies in two different courses. In one course, EGR 270 Continuum Mechanics I, a structure strategy is employed and in another, EGR 100 Designing the Future: Introduction to Engineering, a generative strategy is taught and then used by students. Both strategies are embedded in an instructional context that employs modeling of the strategy on the part of the teacher and also considerable social collaboration. Both modeling and collaboration have been shown to be effective methods, perhaps even critical aspects of the learning context, for helping students learn and incorporate metacognitive skills and knowledge (see Volet (1991)[6], Biggs (1987)[7], Winograd & Hare (1988)[8]).

The structure strategy involves the use of concept maps. Concept maps are not a new phenomenon in education or in engineering education. Smith (1987)[9] argues for the importance of helping (engineering) students understand the nature and structure of knowledge and also an understanding of how humans learn if (the student's) learning is to be meaningful. He finds concept mapping a worthwhile heuristic for helping experts make their own understanding more evident to learners and for helping learners better understand the structure of knowledge. McAleese (1998)[10] finds that using concept maps predisposes learners to consider and make relationships among concepts.

The generative strategy was based on the use of student narratives. In writing a narrative that expresses their understanding of course concepts, students must put those concepts into a form that make sense, that is, that communicates. Doing this requires students to relate course ideas to their existing knowledge. Egan (1986[11], 1997[12]) views teaching as storytelling and finds that the structural (and familiar) features of story or narrative assist students in understanding ideas. Rosen (1986)[13] sees narrative as being a primary and irreducible form of human comprehension. Bruner (1986)[14] finds narrative, the telling of stories, to be the primary mode for humans to express their understanding about the world. Korgel (2002)[15] reports on the use of student journals to promote independent thought and deep levels of understanding in the engineering curriculum.

What follows are descriptions of these instructional practices in the two courses.

CONTINUUM MECHANICS

Continuum Mechanics I, EGR 270, is a four-credit, semester-long course that is largely populated by sophomore engineering students. The aim of the course is for students to develop a strong conceptual understanding and problem-solving skills in a variety of topics related to the mechanical behavior of a continuum. Topics include 2-d and 3-d equilibrium, shear and bending moment diagrams, rigid body dynamics, vibrations, and an introduction to stress and strain.

The Need for Conceptual Maps and Narratives

Introductory engineering mechanics courses apply only a few fundamental concepts (such as Newton's Laws) to a wide variety of mechanical systems. It is all too easy in such a course to teach for and have students learn problem-solving procedures while either losing sight of how these procedures relate to fundamental concepts or never really paying attention to the fundamental concepts in the first place. This type of learning results in students who are unable to apply their knowledge outside of a limited domain of idealized situations; it also inhibits future learning because students do not organize their understanding of concepts in a way that will facilitate continued learning. In addition, it can be difficult for students to see how the details of the content fit together within the course, with other courses and with their own educational goals. By integrating elements of what are often three separate courses—Engineering Statics, Engineering Dynamics, and Mechanics of Materials—into one course and making explicit use of conceptual frameworks to manage the relationships among these elements, EGR 270 is designed to help students see the big picture of how materials behave early in their education. The overarching framework used in EGR 270 represents how the mechanical behavior of an object is related to the loading, material, and geometry of the object. This representation and use of this framework comes in two forms, a conceptual map and a narrative.

Representing ideas and their relationships in explicit ways was not only used to emphasize overall course structure but to illustrate the relationships among ideas in more highly focused ways. Though a course in Newtonian mechanics is a prerequisite, students typically enter EGR 270 not having meaningfully learned the concepts in mechanics and cannot apply them to unfamiliar situations. This is not surprising since most introductory physics textbooks will often devote 10 or more chapters to the subject with little emphasis on how the content presented in those chapters relate to each other. Thus students typically begin the study of engineering mechanics having seen and applied many topics in mechanics, but rarely see how the concepts and problem-solving procedures fit together. When confronted with the non-idealized, real-world problems that face engineers, they often do not know how to proceed. In an attempt to address this, students were provided with a conceptual map, referred to as the dynamics map, to help them understand and apply Newtonian mechanics. The dynamics map was intended to help students organize concepts and provide a starting point for solving problems.

The Conceptual Frameworks

The course conceptual map initially used in EGR 270 is shown in Figure 1. During the process of developing the map several points became apparent. First, there are a variety of ways that the knowledge can be structured and each involves simplifications of the actual complex relationships. The goal is not to develop the most comprehensive map, but the map that most effectively facilitates learning. Second, the development of the map is an iterative procedure that is best accomplished in collaboration with individuals who are not necessarily subject matter experts. Experts often fail to realize the tacit knowledge they possess that needs representation in a map for students. Individuals who understand the nature and purpose of conceptual representations can point out areas that lack clarity or need to be further developed. Third, as students increase their understanding, it is useful to introduce increasingly sophisticated concept maps. Proceeding in this way also serves to decrease the initial intimidation that some students expressed at seeing a course's entire structure represented at the beginning of the semester.

Among the important conceptual features included in this map (see Figure 1) are the following:

- Grouping factors that affect the mechanical behavior of an object into three major areas—material, geometry and loading. These areas are grouped as being internal or external to the object.
- Labeling the nature of the connections between concepts.
- Identifying locations on the map where concepts are quantified.

Several weeks into the course, this initial map was revised. The need for revision became apparent when students were assigned a project to analyze the structural safety and efficiency of the Washington Monument. Their questions and the ways they were putting concepts together required a map that more accurately reflects how an engineer uses the concepts (see Figure 2). The revised map more effectively shows how loading and geometry are combined to calculate internal forces and stresses. The emphasis on grouping concepts as internal and external to the object was replaced with an emphasis on how the concepts are combined in structural analysis.

In addition to the course concept map, a second concept map for dynamics (see Figure 3) was also used extensively. In this map the variables measuring linear and rotational motion are related to each other and to their causes. Because the map relates time-varying forces to time-varying motion, it helps students think beyond the equations of constant acceleration to more generalized motion. It is also useful for illustrating the parallel relationship between the causes of linear motion and the causes of rotational motion. A more detailed description of this map and how it is used to teach physics is given in Ellis and Turner (2003)[16].

Implementation

The use of concept maps began on the first day of class. Before seeing the map, students worked on a group activity listing the variables that affect the structural safety of a bridge. This activity demonstrated both for the teacher and the students themselves that they possessed considerable knowledge of the importance of material, geometry and loading for bridge safety, and also insight into how each affected the safety of the bridge. For example, students identified that the magnitude, direction, and location of the loading are important factors. Many groups also noted more advanced concepts such as the spatial distribution and time-varying properties of the loading as affecting the bridge safety. What the students did not know was how to quantify the effect of each variable (a major course content area) and how all of the many variables were related to each other. After completing this exercise, the class was introduced to the course concept map as the instructor essentially constructed the map by using each of the variables that they listed. This may well have resulted in increased self-efficacy since students saw that their ideas were, in fact, the basis for the course.

Throughout EGR 270 the course concept map was revisited regularly as each new topic was introduced. The purpose of using the map at these times was to help students understand why they were learning each new topic, how the new topic fit in with the other topics already learned and where, conceptually speaking, they were headed in the future. The map was particularly useful for introducing transitions between seemingly unrelated topics. For example, many textbooks jump back and forth between the study of geometric properties (e.g., centroids and moment of inertia) and the study of loading and equilibrium. The concept map helped students properly organize their new knowledge.

Because the course concept map helps student see the big picture, it is most useful when students work on big-picture activities. For example, the Washington Monument project required students to synthesize all of the concepts presented in the course and apply them to a complex, real-world situation. Devising an analysis strategy and sorting through available data for relevance are two of the major challenges that face students as they begin the analysis. Because these are big-picture issues, the concept map helped bring order to what would otherwise have been an overwhelming amount of data, equations, and concepts. The map was referred to constantly by the instructor and the students during any presentations, discussions, or extra help sessions relating to the project. Thus in addition to serving as an organizing tool, it also served as a communication tool by providing a common reference for everyone.

Another major use of the course concept map was to help students understand where assumptions and idealizations occur and their effects on other variables. For example, Figure 2 shows that stress theories are used to quantify the relationships used to compute stress distributions from the internal force/moment distributions and geometry. As students continue in their education, they will learn increasingly sophisticated stress theories that will result in more realistic stress calculations. Because the flow of calculations in Figure 2 is from bottom to top, it is clear that changing stress theories will affect the computation of an object's behavior. These theories will not, however, affect variables that are lower on the map (such as the distribution of internal forces/moments).

The more focused dynamics map (see Figure 3) was used as the focal point of a review of Newtonian mechanics and as an aid for solving rigid body dynamics problems. To solve problems, the students used the map to locate the variables that were given in the problem statement and that needed to be calculated. The path between the variables was then identified as the solution procedure. For example, if the forces on a tire with a fixed axis were given and the angular displacement needed to be found, the solution path would be to (1) draw a free-body diagram to calculate τ_{net}, (2) relate τ_{net} to α using $\tau_{net} = I\alpha$, (3) integrate α to find ω, and (4) integrate ω to find θ. They could also choose an alternative solution procedure by taking the impulse-momentum path relating τ_{net} directly to ω. In fact seeing that either path could be used for solving problems surprised many students who entered the course not understanding the relationship between Newton's Second Law and impulse-momentum. Although students had never seen the map in a physics course, they still chose to use it extensively. When presenting solutions in class, solving homework problems or asking questions in class, the map was constantly referred to by the instructor and teacher. Again, because of the complexity of applying theory to real-world projects, the map proved to be particularly useful in a project requiring students to videotape and analyze their own motion.

Evaluation

All 27 students were asked to complete a pre- and post-course attitude survey, a mid-semester survey on the effectiveness of the instructional strategies used in the course, and a post-course survey on achievement of course goals. Two student focus groups covering all aspects of the course were also convened at the end of the course. All the evidence indicated that most of the students had a positive experience in the course. Students generally perceived that the educational objectives for the course were met (see Table 1). Student confidence increased dramatically. At the beginning of the semester only 11% of the students in the class agreed or strongly agreed with the statement, "I feel confident in my skills, abilities, and knowledge in engineering." At the end of the course, 81% agreed or strongly agreed. The number of students who agreed or strongly agreed with the statement, "I am committed to a career in engineering" rose from 56% to 69%.

Students perceived Objectives 1, 2, 3 and 5 to be the most effectively achieved. These were also the objectives in which concept maps played the largest role. But how much of the success in meeting these objectives was due to the use of conceptual frameworks? In a mid-semester survey students were asked to rate the effectiveness of a variety of instructional strategies used in the course. Their responses for the course concept map and narrative and the dynamics concept map are shown in Table 2. The majority of students found both maps to be helpful. The course concept map and narrative were often mentioned as helpful for seeing the "big picture." Their helpfulness for showing direction, providing perspective, telling why you are doing things, and providing a sense of what the class is about from the beginning were also mentioned. Only two students expressed a negative opinion—one thought that they were confusing and the other did not think that they were useful. Student response to the dynamics concept map was more effusive as students used terms like "extremely" and "very helpful" more often than for the course concept map and narrative. The dynamics framework was cited as being useful for showing the relationships among formulas and concepts, synthesizing information, clarifying concepts, and setting up problems. No student expressed a negative opinion of the dynamics concept map.

At the end of the course two focus group meetings were held, consisting of 5 and 7 students and led by a moderator unconnected to EGR 270. Although the focus groups discussed many aspects of the course, they were specifically asked to comment on the course concept map. Typical comments on its use are:

"Yeah, he used that a lot…When we would go to different topics, like we'd start a new unit…he would just relate back to it…and see where we're going in the math, and things could be related to when we get to fluids and materials…it was helpful."

"I think the concept map is…in your head, where you just suddenly click: oh, everything is linked!"

"It was nice to see that what you were doing was actually…something to be used later on that you would need, not just doing something with no end, no goal…"

"…the fact that he keeps on bringing it back in—after a while you're like…I'll listen to what you're talking about. And it is helpful… I think now, at the end of the course, it definitely makes perfect sense to have that."

One student compared her experience in EGR 270 to a course in materials that she had taken at a university. She describes the university course as:

"It's on materials…and all the professor does is tell us how to read a graph and then derive equations, and you derive equations for an hour every day, and he doesn't ever tell us what they're for…"

And then compares it to EGR 270:

"And in this course [EGR 270], you always know what you're doing, and he makes a point at every new chapter to go through the concept map and [says] 'so we learned how to do this, which means we can now do this, which relates to this, and it makes everything make sense.' So you're able to say, 'Even if I don't understand the math, this is what it's for.'"

One common concern raised by a number of students in the focus groups was that it was intimidating to start the course with the map. One said,

"At the beginning of the course I was nervous about the concept map, because half the words I didn't even understand, so I knew that it wasn't until this point [the end of the course] that I would actually get it."

Another student commented,

"It has to be introduced at the beginning. You have to know what all these things are that this course is [going to] cover; whether or not it's overwhelming is irrelevant, because you do cover all of that. But there is no way to introduce it in which I wouldn't immediately discount it and then later on realize that it was important."

Summary and Conclusions

A concept map and narrative illustrating the relationship between the mechanical behavior of an object and the factors that affect that behavior were used to help students organize concepts presented in an introductory continuum mechanics course to see the big picture. A second concept map on dynamics was used to help students integrate the dynamics concepts and provide guidance in solving problems. Students perceived both maps as being helpful in their learning.

INTRODUCTION TO ENGINEERING

EGR100 is a four credit, semester-long course intended for first year students interested in engineering. The aims of the course are for students to develop a sound understanding of the engineering design process through a semester-long team-based design project; to be able to apply formal design tools and work effectively in teams; to effectively communicate ideas, designs, and analyses orally, visually, and in writing; to begin to consider the impact of engineering in a global and societal context; and to develop ones own views on the nature of engineering. For a detailed description of the course and its design component please see Mikic & Grasso (2002)[17]. This year, fifty students enrolled in EGR100, and the course was taught by four instructors, each assigned to one of four sections. Each section used the same assignments, format, and grading rubrics. Instructors met on a weekly basis to discuss course logistics, delivery, and grading issues.

Purpose of and Instructions for Narratives

In prior years, students had expressed concern that the majority of their course grade was dependent on group work. In an effort to provide greater opportunities for individual student work, students were asked to write a narrative essay on the nature of engineering. Specifically, students were instructed as described in Figure 4. The two essential elements of the narrative were that students attempt to describe their current views on the nature of engineering as well as how they see themselves in relation to this field. In particular, students were encouraged to articulate their "big-picture" educational and life goals, and how they believed engineering might be an appropriate vehicle for achieving these goals. Students were also told that it was expected that these views would evolve over the course of the semester and beyond.

While one expressed purpose for using the narratives was as an assessment instrument, the other purpose was more instructional in nature. By asking students to reflect on and express the state of their knowledge, the narrative called attention to the importance of constructing meanings that encompassed all the content of the course and, moreover, related that content to their existing knowledge.

Implementation and Evaluation

Students were required to complete three versions of the essay. The first version was due during the second week of class, the second at mid-semester, and the third during final exam week. Only the final version of the narrative received a grade, although all three versions received extensive written feedback from the instructor. The official grade on the assignment was meant to reflect the extent to which a student's thoughts, level of sophistication and breadth of issues addressed changed over the course of the semester.

Assessing something like a narrative is challenging. To help with this, the instructor in one section used the assessment rubric shown in Figure 5 as a way of evaluating changes that occurred between the first and third versions of the narrative. The rubric addressed three main areas: (1) writing style; (2) content indicators; and (3) metacognitive indicators. Writing style scores were based on the extent to which the narrative was written as a coherent essay rather than a collection of random thoughts and ideas. Content scores assessed the extent to which the following topics were identified as being relevant to engineering: communication;

design/creativity/teamwork; analysis and problem solving; ethics/professional responsibility/societal context and impact; basis in math and science; breadth of activities and roles for engineers; and the level of sophistication of response (nuanced vs. black/white). Lastly, metacognitive scores assessed the following reflective practices as exhibited within the narrative itself: articulation of ones own values and goals for what she hopes to achieve with engineering; identification of potential conflicts between ones own values and those perceived to exist within the larger culture of engineering; connections made to ones own life experiences; connections made to non-EGR100 engineering topics and examples; connections made to the curriculum (engineering or otherwise); and self-identification as an engineer/development of a sense of ownership. First and final versions of all fourteen narratives in one section were evaluated using this rubric. In addition, all fifty students were asked in the anonymous end of semester survey to assess the educational value of the narrative essay.

Student Perceptions of Educational Value

Overall, EGR100 students rated the educational value of the narrative essay as follows: 10% gave it zero value, 10% rated it as low, 43% medium, and 37% as high. Breakdowns were comparable in all four sections. Interestingly, even students who rated the educational value as low expressed in their comments that the assignment was valuable. For example, two 'low' raters commented;

"'Educational value' was low. They had a lot of value in encouraging me to reflect on my future as an engineer in a more personal way."

"The narrative essay allowed for me to reflect on my thoughts on engineering and re-evaluate my choice of career. Aside from personal thinking and evaluating, the essay was not teaching me anything new."

It seems likely that students interpreted "educational value" to mean directly connected to the problem solving work of the course.

More representative comments included the following:

"Makes me think more critically about my reasons for wanting to be an engineer"

"Good … evidence of obvious development of concept of engineering and how it relates to us individually."

"I enjoyed this … and learned a lot through the process"

"I can see myself progress through writing the narrative essay"

"It taught me a lot about myself"

"It definitely helped me understand engineering as a whole, as well as my part in it"

"I enjoyed writing the narrative in sections throughout this course. I thought that in doing so I could tacitly view how my perceptions on engineering had changed and developed."

Measures of Improvement

In Figure 5, the mean ± standard deviation of scores on the assessment rubric are shown for the first and final versions of the narrative. Data were analyzed statistically with a one-factor ANOVA, where version-of-essay was used as the independent factor. Overall, the total score increased significantly between the first and final versions by 71% ($p < 0.0001$). Writing scores increased by 43% ($p = 0.0004$), total 'content' scores increased 48% ($p < 0.0001$), and metacognitive indicator scores increased by a notable 134% ($p = 0.0003$). It is interesting to note that, of the content categories assessed, only communication, ethics/societal impact, and the sophistication of response increased significantly over the course of the semester. All other areas (design, analysis, math/science, breadth of roles) were not significantly greater by the end of the semester than at the start because students tended to include these components in their initial descriptions of the nature of engineering. By contrast, all metacognitive indicators assessed increased significantly (73% - 343%), with the exception of 'making connections to events in ones own life' which increased by 40% but was not statistically significant ($p = 0.2557$).

Correlation to Course Grades

We were also interested in determining whether components of the final (version 3) narrative scores could serve as predictors of overall student course grades. Simple linear regression analyses were run with course grade (not including the narrative essay component) as the dependent variable, and total narrative score, content score, and metacognitive indicator score as the independent variables (each model was run separately). Overall, the best individual predictor of course grade was the metacognitive indicator score ($R^2 = 0.34$, $p = 0.0278$), with total narrative score explaining only 3% more of the variability in course grade than the metacognitive score alone ($R^2 = 0.37$, $p = 0.0199$). By itself, the content score explained less of the variance in the course score than did the metacognitive score ($R^2 = 0.29$, $p = 0.046$). When metacognitive score and content score were analyzed as covariates, the two together did not significantly outperform metacognitive score alone as a predictor of student course grade ($R^2 = 0.36$). Thus, metacognitive indicators appear to be statistically significant predictors of how well a student performed in EGR100. Although the coefficient of determination (R^2) is less than 40% in all cases, these numbers are fairly high when one considers that 75% of the course grade (without the narrative essay) is based on some form of group (rather than individually produced) work.

Qualitative Examples

Perhaps the most effective evidence of student growth in understanding the nature of engineering and how they see themselves in relation to it comes from the narrative essays themselves.

Example #1

In her first essay, student #1 writes, "The Webster dictionary defines engineering as the application of mathematics and science by which the properties of matter and the sources of energy in nature are made useful to people." She goes on to describe her experiences with the FIRST robotics competition in high school, working alongside professional electrical engineers, concluding, "I formed ideas of what it was to be an Electrical Engineer, I thought and still think that it involves circuitry and programming exclusively. Due to my bias, I maybe am limiting myself to one form of engineering without properly disqualifying the other subdivisions." She concludes her essay with, "I joined the Smith Engineering program in hopes of discovering my specific love of the trade."

Student #1 begins the final version of her narrative as follows: "One day during class Professor Mikic pointed out that our class spoke of engineers as they, them, he, she, or engineers, but never as I or we. I think it was that day when I started to think of my place in engineering. Now as I think back to the fifteen weeks I spent in the Introduction to Engineering course I realize that…I formed my own definition of engineering while working through three components of the course…[which served as] stepping-stones to me defining engineering and finding my place in the field." The first transformation this student describes is her developing sense of ownership and belonging to a community: "When giving the presentation of the final report I realized that a lot of the impersonal expressions disappeared during the presentation. I started making statements like 'we as female engineers are underrepresented in the field' and 'being a minority in engineering…' These statements surprised me, but it allowed me to see that I was making engineering my own, something that was tangible. In a sense it was no longer an unobtainable goal it was something that I could reach with the proper direction." The second transformative experience this student describes is working with her community collaborators for the design project (a local 6th grade science teacher and her students). She comments, "This made me realize that engineering is a field that I want to continue to pursue, not because of the amount of money I will make, but based on the fact that I am making something to help or improve a person's life. I also think that the concern of human life is a result of learning the beginnings of engineering at a liberal arts institution rather than a school of engineering." To conclude her narrative, this student returns to the Webster dictionary definition of engineering, but does so in order to move beyond it: "The stated definition is very general and through my experience in Introduction to Engineering I was able to form my own definition. Engineering is applying scientific and mathematical principles that are appropriate for the community [for which] the design is being created in the hopes of making a useful tool for [that] community."

Example #2
Student #2 began the semester with a fairly sophisticated response to the narrative essay assignment, but demonstrates in her final version that she is thinking more deeply about many new issues that she associates with the choice of being an engineer. For this student, one of the most pressing issues had to do with what it would be like to be a woman engineer: "At the beginning of the semester, I was especially concerned about how it will feel to be a woman working in a male-dominated field. I wonder, how will people respond to me as a woman engineer; will they still treat me with respect? I have no idea what kind of discrimination, if any, I will face. I was especially thinking about this issue when we were discussing the Citicorp tower. I thought to myself how horrible it would be to be in [Le Messurier's] place, and how much more horrible it would be to be in his place as a woman. I imagined my face turning red while I admitted that I had helped to design a building now in danger of collapse; would my mistake be blamed on the fact that I am a woman? Would the public laugh at the woman who tried to be an engineer and wound up designing a defective building? And would people's confidence in women engineers decrease? It seems like not only would I have the terrible responsibility of many people's safety, but I would also be carrying the responsibility of

representing other women engineers…Nevertheless, since coming to Smith, I also realized that I have been thinking about my role as a woman engineer in the wrong terms…I should not be a woman trying to 'sneak' into a world dominated by men, hoping to somehow let it go unnoticed that I am different from men; instead I should (ideally) be able to go into engineering with the full assertiveness and confidence of a woman ready to bring new perspectives to the field."

This student goes on to raise many issues with which she is currently struggling, including whether or not the engineering curriculum gives her enough academic freedom to explore other areas to the extent that she feels she needs to be a well-rounded thinker: "When we talked about the 'two cultures' of science and the humanities, it seemed like we focused on the need for dialogue between the two, but we did not talk enough about the need to *fully develop ourselves* in both areas. I wonder if such a balance is even possible in our society, or if it is, how talented must someone be to achieve it?" Later she reflects on the ethical responsibilities of engineers: "I realized that even a seemingly benign advancement such as a steam-powered car could greatly exacerbate the poverty levels in some developing countries' oil-dependent economies. How … can one address an ethical issue so complex as to entail weighing the value of future environmental stability (and consequently people's future quality of life) against the value of people's quality of life today? I wonder what ethical issues I may face, and how appropriately I will address them." As the semester unfolded, this student found her interests in environmental engineering growing to the extent that the passion she feels for making a difference in the world through environmental engineering begins to outweigh the many uncertainties and fears she has identified. She writes of one guest lecture in particular: "The … lecture invigorated me so much that I have hardly even thought about my engineering-related insecurities in the last few weeks." She concludes her essay with confidence: "Though my anxieties and insecurities of course still exist, I am trying to focus on the fact that I truly feel I made the right decision in deciding to be an engineer. I really want to become more involved in environmental issues on a scientific level, and I am trying to focus on that goal more than on any nasty speed bumps I may hit on the way. Besides, maybe those aspects of engineering that sometimes worry me, such as the discrimination I may receive…may also become opportunities for accomplishing some good."

Example #3

Another common theme raised by students was their desire for socially responsible, meaningful work. In her first essay, one sophomore discusses her initial choice to be a physics major because of her love of math and science, but then adds, "my new involvement in social justice convinced me that I wanted to work towards improving lives more directly than a physicist might…So after pondering my potential life as a physicist, I decided that I wanted more social responsibility. From the little that I've heard and read, engineering might be the right mix of math, science, and social responsibility."

In her final version, this student quotes from readings from her humanities and a social science classes as she outlines the various considerations that an engineer must have. From social theorist Harold R. Kerbo, she concludes that "with new technologies come people without those new technologies…In addition to accessibility and affordability, engineers must keep in mind that what is best for some is not best for all." Drawing on the work of Vandana Shiva, a world-renowned environmental activist and one of India's leading physicists, this student writes that "Engineers working with 'less developed' countries must have cultural sensitivity and a deep understanding of the area's structure before designing and/or installing new technologies." Next, she moves on to discuss the absence of engineers from politics and states that "We should heed [C.P.] Snow's warning about over-specialization, and rid ourselves of the notion that an engineer's job is simply to design and build machines while letting others decide where and why." Finally, she concludes: "these are my current views on the engineer's role in society. Technology can help society, I'm sure. I just need to determine how. I hope that with engineering, I can … [work on] problems knowing that if I come up with a reasonable, correct solution, it will be the source of some societal change, be it large or small, that will benefit people equally."

Example #4
Initially, student #4 began with a very simplistic view of engineering in her first essay: "I was first drawn to Engineering when I heard it involved my two favorite subjects, physics and math. Aside from that, I thought it would be cool to wear a hard hat and boss people around on construction sites. As I begin to learn more about engineering I realize the vast opportunities that are in this field, from Environmental Engineering to engineering the atom bomb. There are a lot of really incredible things that engineers do, but also a lot of dangerous and scary things that engineers participate in."

By the end of the semester, this student chooses to focus on three specific aspects of engineering: "communication, working with a team, and developing a social conscience. By focusing on these three aspects I hope to become a well-rounded engineer, and find the field of engineering that is right for me." After discussing why she views these topics to be germane to engineering, she writes, "Communication, teamwork and social consciousness are three aspects that I see as continuing to be important priorities as I begin to pursue a career in the engineering field. In the Introduction to Engineering class this semester I was challenged by the techniques of proposal writing and oral presentations to improve my ability to constructively convey my ideas to other people. I grew through my involvement with a team that demanded I put forth my best effort. I developed my place within this team, and learned how I can work best with a group of people who think differently from me. At Smith College I am exposed to political and social discussions which help me to develop my opinions on issues that could affect what type of engineering I pursue."

Example #5
For this student, at the start of the semester, engineering involved "applying math and science to situations" but could "also be more product-oriented." She discussed her involvement with FIRST robotics in high school, and her desire to have "a job that has some meaning outside my office building." By the end of the semester, she reflects: "Since I have come to Smith, I have continued learning about engineering in general, but I have also started to learn about the societal context of engineering and to examine how my own goals and values might relate to a career in engineering…While the engineering culture certainly falls within the scientific culture, I believe that in engineering there is much overlap into the humanities culture. It is important for engineers to know about the world for which they are designing products. I think that this is the importance of studying engineering at a liberal arts college. While graduates of a more technical college may have a better knowledge of the details of engineering, I will know the basics of engineering, but I will also have a context for my work. I will be able to think both about designing the product and

about the societal impact the product will have. In addition, while the specific technical details will change, the basic principles will remain the same. This holistic view of engineering is one of the elements that attracted me to [it] in the first place." As she "began to think about [her]self as an engineer," her vision of engineers came across as an extremely positive group with which to identify: "When I think of engineers that I have seen, I think about strong, creative, knowledgeable people sharing ideas within their team to achieve a common goal."

Example #6
In this final example, the student chose to take a more creative approach to the narrative. She sets the scene: "The year is 2020. I'm sitting in front of the fireplace with my eight year old daughter, Eva. We stretch out our cold toes and wiggle them to heat them up. 'Mummy, how was work today?' Eva asks me. 'It was great,' I answer honestly. I do love my job. I work with a lot of different kinds of people. We all have different knowledge backgrounds, but we all have the same purpose: we are engineers. 'Mummy, what's an engineer?' she says." The scene unfolds with Eva's innocent questions providing opportunities for the future practicing engineer to articulate her views on the nature of engineering and how she is achieving her goals. In one passage, the mother explains the importance of diversity and teamwork: "If I worked with a lot of other mechanical engineers, our ideas wouldn't have the same variety that the ones at my work do. It would be like if your … teacher was asking everyone what their favorite color was, and then you had to make a painting out of everyone's favorite color, but everyone's favorite color was purple, so the painting was just purple and boring. But in my company it's as if we all have different favorite colors, because we all know a lot about different things. So our painting can be really interesting."

Narratives and Choosing to Major in Engineering
Based on the dramatic increase in students' development of a sense of ownership and self-identification as engineers by the third version of the narrative (+247%), we hypothesized that, compared to prior years of EGR100, the current year's class might exhibit an increase in retention indicators. In 2001-2002 (when no narrative essay assignments were used), 78% of 59 students indicated that when they enrolled in the course they had intended on majoring in engineering, while only 66% indicated that this was still the case at the end of the semester. In the current academic year, a comparable percentage of students (79%) indicated that they had intended on majoring in engineering when they enrolled in the course, whereas 85% indicated this was still the case at the end of the semester. While larger sample sizes are required to examine whether the use of narratives can aid in students' sense of belonging and, ultimately, retention, our preliminary data are intriguing in this regard.

Summary and Conclusions
In summary, the use of narrative essays in our Introduction to Engineering course appears to be a valuable tool for assessing the evolution of students' thoughts on the nature of engineering and how they see themselves in relation to the field. Specifically, metacognitive indicators (as evaluated in the narrative essay) increased dramatically over the course of one semester, suggesting that students are developing the skills of reflecting on their learning in relation to their broader educational and life goals. Scores on the final version of the narrative essay were positively and significantly correlated to overall course performance, with metacognitive indicator scores providing a better correlation to course performance than engineering content

scores. The majority of students viewed the educational value of the narrative essays to be between "Medium" and "High," with all students perceiving some value in the activity even if they did not view it as 'educational.' Perhaps more important than their use as an assessment tool, the narrative essay provides a mechanism for students to draw connections between their curricular activities, engineering in general, and their own personal goals and values. Students' sense of ownership and belonging to the community of engineering increased significantly over the course of the semester and may be linked to indicators of intention to persist in the major. We plan on asking students to revisit their first year narrative essays at the start and end of senior year as a way of assessing the continued evolution of their views on the nature of engineering throughout their undergraduate years.

Discussion

We are much encouraged by what we have seen as a result of using conceptual maps and narratives. Both of these instructional tools have helped move students toward a more inclusive, inter-related, and meaningful understanding of the material they are encountering in these engineering courses. Further, we believe that student thinking will continue to be affected by these strategies beyond the specific courses. We recognize that these finding are preliminary. However, in our minds, they justify refining, continuing to use, and even expanding their use. Among our next steps will be to collect more and better evidence on the effect of using these strategies.

Acknowledgement

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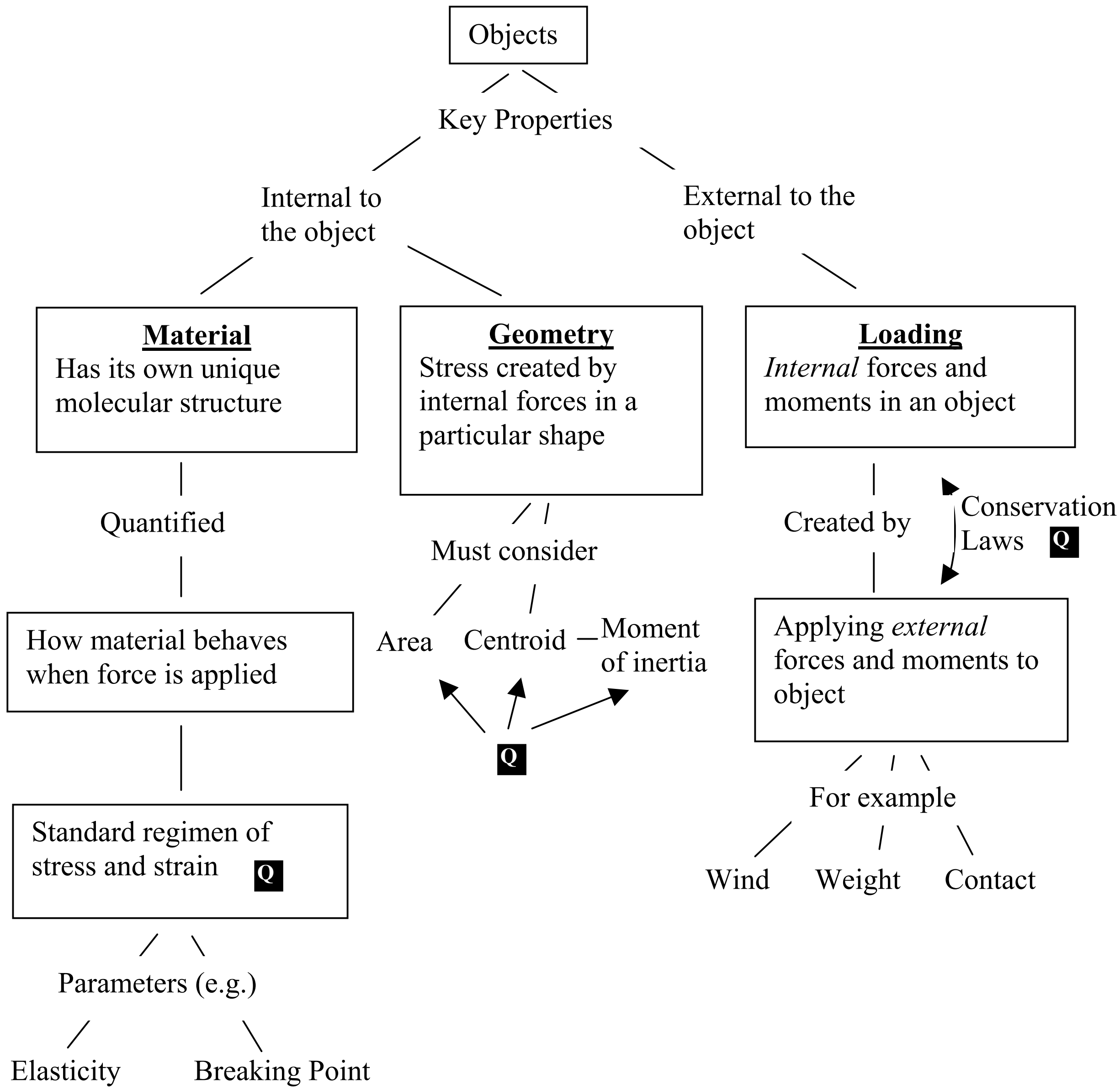
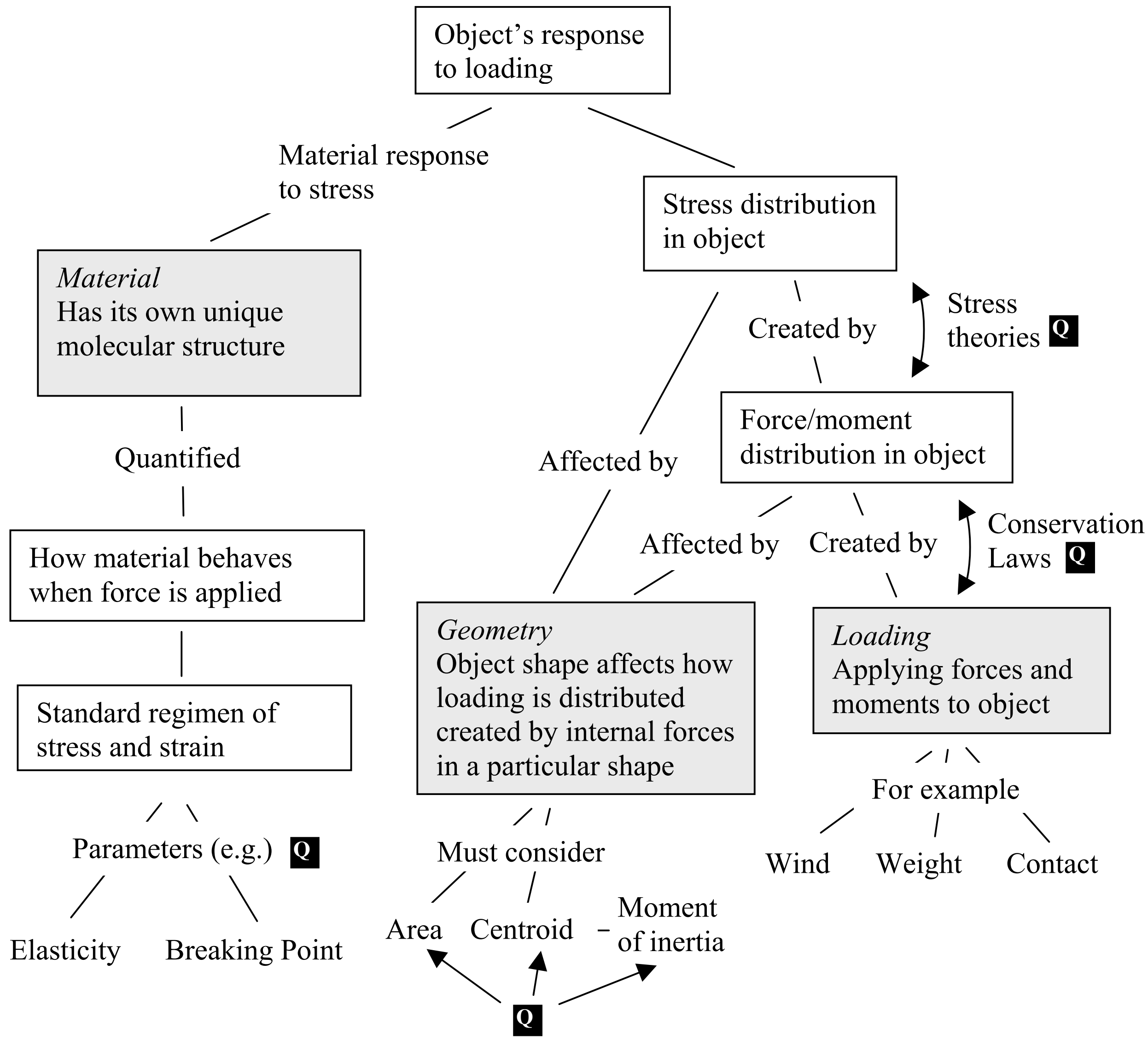


All concepts are related in complex ways.
Using formulae, algorithms, procedures and conservation laws we can quantify these key properties. Quantification represented by Q
Purpose? So we can effectively use objects in the engineering design process.

Figure 1: Course concept map used in the beginning of EGR 270.

EGR 270 Concept Map

In EGR 270 you will apply and build upon what you have already learned in physics, chemistry and calculus to understand how matter responds to forces. This map focuses on the relationship of the three factors—material, geometry, and loading—that affect the response.



All concepts are related in complex ways.
Using formulae, algorithms, procedures and conservation laws we can quantify these key properties. Quantification represented by Q
Purpose? So we can effectively use objects in the engineering design process.

Figure 2: Advanced course concept map used toward the end of EGR 270.

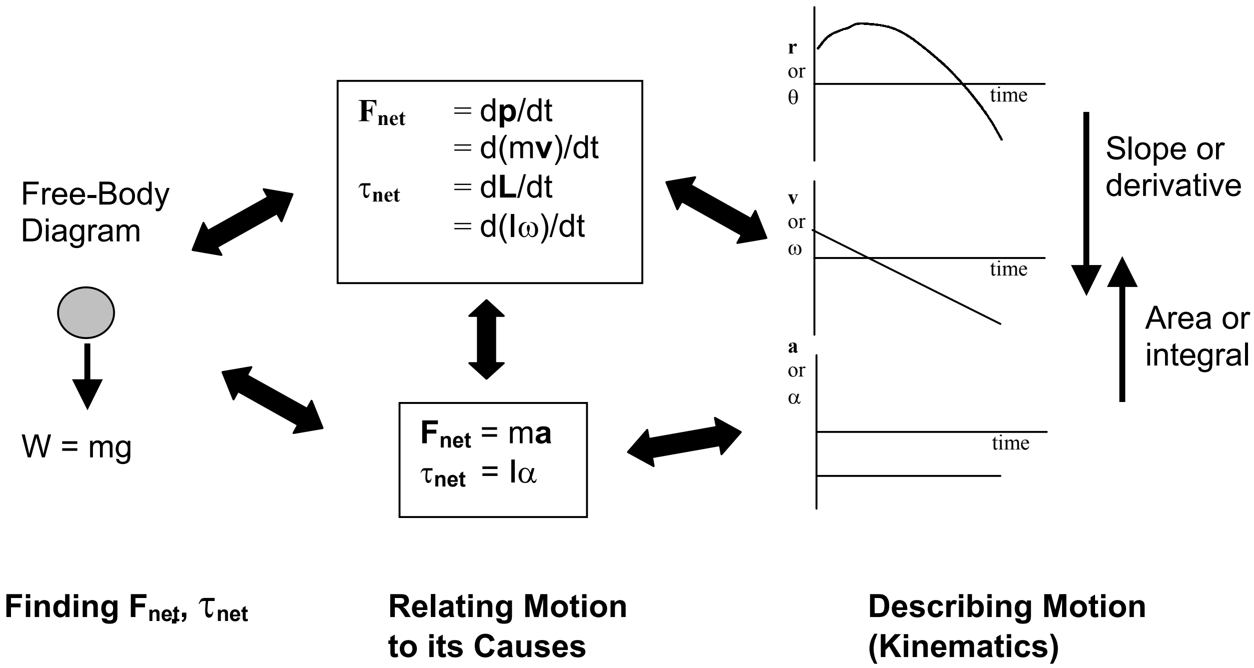


Figure 3: Dynamics concept map used in EGR 270.

	Learning Objective	**Mean**	**Standard Deviation**
1	I have developed a conceptual understanding of how loading, geometry, and material properties affect the mechanical behavior of a continuum.	4.56	0.51
2	I have developed problem solving competence based upon fundamental principles in calculating internal and external forces for statically determinate 2D and 3D mechanical systems in static equilibrium.	4.60	0.58
3	I have developed problem solving competence based upon fundamental principles in calculating internal and external forces for calculating centroids.	4.32	0.63
4	I have developed problem solving competence based upon fundamental principles in calculating internal and external forces for describing the behavior of damped and forced vibrating systems.	3.28	0.79
5	I have improved my understanding of calculus and physics through their application.	4.36	0.95
6	I have improved my skills in oral, written and visual communication.	3.64	1.11
7	I have improved my ability to work effectiely in a team.	4.12	0.83

Table 1: Student perceptions of achieving each of the EGR 270 learning objectives (Based upon the responses of 25 of the 27 students enrolled in the course.)

Student	How helpful is it?	
	Course Concept Map and Story	**Dynamics Concept Map**
1	shows direction of course which is good	extremely helpful! Helps show how all those formulas and concepts are related which helps me to understand new ones based on old ones I'm already confortable with
2	extremely	extremely
3	confusing	?
4	very helpful	very helpful
5	a good reference to keep in mind as the course goes on. Puts things into perspective	Puts the class and semester into an easy to understand form. We always know where we're going
6	It was very helpful in outlining EGR education	helped to synthesize imformation
7	nice! Definitely helped to see the big picture	really great? One method of looking at all that type of problem
8	helpful but not sure how book follows map. Maybe add chapters to map	helpful but I wish I had a review of integrals first
9	I like maps	what is this?
10	It was okay. I don't know idf the map is really that important.	I think it's really important
11	it is interesting, especially to keep the big picture in mind	extremely helpful
12	helpful	very helpful
13	very helpful to see the big picture	very to see how everything fits together
14	most classes just dive right in, but this actually tells you why you're doing what you're doing—very helpful	very! It's great to be able to fall back on the basic F=ma when I'm struggling with a problem. The graphs are very helpful also
15	it's nice to visually see how this course fits into the big picture	this was very helpful for me to understand how to set up every problem. I think it's a very good approach for this class
16	it's good to have a sense of what this class is about at the beginning of the semester	very helpful in clarifying the concepts
17	pretty helpful in understanding the big picture	
18	they were fine, but not very useful	good reference
19	seems necessary	necessary

Table 2: Student perceptions on the helpfulness of conceptual frameworks used in EGR 270 (Based upon the responses of 19 of the 27 students enrolled in the course.)

EGR100 Engineering Narrative

A 1998 HARRIS poll found that 61% of adults in the United States are not well informed about Engineering. One goal of this class is for each student to develop an understanding of the nature of the engineering profession. Your perspective on this will naturally evolve during this semester, over the next four years, and beyond. In this assignment, you will write a thoughtful narrative which expresses your current views on the nature of engineering and how you see yourself in relation to this field.

Why a narrative? Narrative communication (i.e. story-telling) is a powerful tool that people of all cultures use to communicate their understanding of the world around them. By developing a narrative about the nature of engineering, you will be engaged in a creative act that will help you to organize your thoughts about the subject of this course (and, perhaps, your major and your future career). This narrative assignment is about telling a two-part story. The first part is about the question: what is engineering? The second part addresses how you see yourself fitting in to that story. What are the central themes of this discipline, and how are they relevant to your own personal values and goals? Such a story will help you make sense of this vast area, and, more importantly, provide a framework within which you can begin to piece together the ways in which different components of your education fit together as part of a greater whole.

This narrative is due in class on Sept. 12, and revised versions that reflect your changing perspective will be due on Nov. 7, and during the final exam week.

Figure 4: Instructions given to students for Narrative Essay in EGR100.

EGR100 NARRATIVE ESSAY RUBRIC			
Topic	**Version 1**	**Version 3**	**Change**
I. Writing Style (10 pts) Coherent essay takes reader to a destination vs. random collection of thoughts or ideas	5.29 ± 1.68	7.57 ± 1.22	+43%*
II. Nature of Engineering Content identified:			
Communication (5 pts)	0.43 ± 0.85	2.71 ± 1.90	+530%*
Design/Creativity/Teamwork (5 pts)	3.07 ± 1.27	4.00 ± 1.36	+30%
Analysis/Problem Solving (5 pts)	1.86 ± 1.51	2.57 ± 1.65	+38%
Ethics/professional responsibility/societal context & impact (10 pts)	3.50 ± 2.50	6.79 ± 2.75	+94%*
Basis in math and science (5 pts)	3.36 ± 1.34	3.29 ± 1.68	-2%
Breadth of activities/roles encompassed by 'engineering' (5 pts)	2.93 ± 1.49	3.14 ± 1.51	+7%
Sophistication of response (nuanced vs. black/white) (10 pts)	4.21 ± 1.58	6.07 ± 1.98	+44%*
III. Identifies own values/goals for what she hopes to accomplish with engineering (10 pts)	2.93 ± 2.30	5.07 ± 2.56	+73%*
IV. Identifies potential conflicts between own values and those she perceives to exist in the culture of engineering (5 pts)	0 ± 0	1.57 ± 1.99	N/A*
V. Connects to events in her own life/own experiences (10 pts)	3.71 ± 3.05	5.21 ± 3.74	+40%
VI. Connects to other engineering topics or examples (10 pts)	1.00 ± 1.75	3.07 ± 3.27	+207%*
VII. Connects to curriculum (engineering or broader) (5 pts)	0.79 ± 1.12	3.50 ± 1.40	+343%*
VIII. Self-identifies as an engineer/has a sense of ownership (10 pts)	1.21 ± 1.37	4.21 ± 2.58	+248%*
TOTAL:	34.3 ± 11.7	58.8 ± 13.8	+71%*
TOTAL CONTENT SCORE (II):	19.4 ± 5.27	28.6 ± 4.54	+47%*
TOTAL METACOGNITIVE INDICATOR SCORE (III-VIII):	9.64 ± 6.38	22.6 ± 9.73	+134%*

Figure 5: Evaluation rubric for narrative essays (versions 1 & 3) in one section of 14 students in EGR100. Data indicate mean ± standard deviation. (* $p < 0.05$).

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