Adapting Entry-Level Engineering Courses to Emphasize Critical Thinking

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Abstract

The University of Louisville recently developed a Quality Enhancement Plan (QEP) to improve undergraduate instruction across all disciplines as part of its ongoing accreditation requirements. Central elements of the plan are emphasis on critical thinking, integration of critical thinking throughout the curriculum, service learning for undergraduates, and a culminating experience. With the adoption of the QEP, instructors were asked to incorporate these concepts into their curriculum. One of the most interesting efforts in revamping course presentation has been to change the way a truly fundamental course, Statics, is taught.

In order to modify the existing Statics course to meet the QEP objectives, minor changes were necessary in the areas of course design (course objective, culminating experience, flowchart of progress) and assessment procedures (pre-quiz, group problems, and optional final). The changes were not extensive, but rather only minor changes to presentation or organizational format. Statics is one of the core courses within the engineering curriculum and a significant amount of information must be conveyed and mastered. Thus, the changes presented do not disrupt the normal classroom flow, but rather shift the emphasis and language to incorporate critical thinking explicitly.

To assess the effect of the modified course curriculum, data from four separate instructors covering 15 different classes and 672 students between 2004 and 2008 were compiled to identify baseline performance. Data compiled included not only final grades but also individual test scores associated with specific concepts. This information was compared to the Summer 2009 class (115 students) in which the course modifications were enacted. The exam questions presented were almost identical to those used in previous semesters to enable direct comparisons.

Based on the data, after a slight shift in the focus of the class and the incorporation of critical thinking concepts, a marked improvement in student performance and attitude was observed. Thus, by repackaging the Statics course content to emphasize the goals established by the QEP, improved student interaction and understanding can be achieved. It is not always necessary to make broad sweeping changes to a course, but rather it may be beneficial to make a variety of little, incremental changes.

Keywords: ACCREDITATION, critical thinking, innovation, teaching methods.

Introduction

As part of The University of Louisville's accreditation by the Southern Association of Colleges and Schools (SACS), the school has worked to develop a Quality Enhancement Plan (QEP) for improvement in undergraduate instruction. Through this review of all academic courses and programs the QEP identified four specific areas of instruction that needed improvement: 1) gaining the ability to solve problems and to apply theories in practice through critical thinking; 2) integration of learning (no more outlier courses unrelated to any other course or practice area); 3) opportunities to apply classroom learning in practical experiences through service learning; and 4) taking learning out to the community through a culminating experience to synthesize knowledge through practice that benefits the university and the community.

The concept of critical thinking has been defined many times over the past forty years, but generally includes activities focused on key abilities: to question; to acknowledge and test previously held assumptions; to recognize ambiguity; to examine, interpret, evaluate, reason, and reflect; to make informed judgments and decisions; and to clarify, articulate, and justify positions (Halpern, 1996; Holyoak, 2005; Kitchener, 1986; Palmer, 2004; Pascarella, 1991; Ruggiero, 1975; Scriven, 1976; Scriven & Paul, 1976). Paul and Elder (2001) developed a learning paradigm that divided these activities into three fundamental areas: 1) analysis of thinking by identification of elements of thought (e.g., questions, purposes, inferences, etc.); 2) applying intellectual standards such as clarity, relevance, and accuracy; and 3) consequent development of intellectual traits desired in undergraduate students. This Paul-Elder framework should be familiar to engineering educators and practitioners as it provides the basis for organized thinking and a logical progression to a problem solution (Smith, 1977).

Implications for Engineering

With the development of the QEP and adoption of the Paul-Elder framework for critical thinking, instructors were asked to incorporate these concepts into their curriculum. Interestingly, incorporating the QEP mission into the engineering curriculum proved both more and less challenging than originally anticipated. As an example, when faculty members in the School of Engineering were asked for their reactions to the QEP and the subsequent implementation plan, their universal reaction was, "But I already do that." All of the faculty members interviewed expressed the feeling that critical thinking is essential to engineering and is routinely emphasized in classroom presentations, homework problems, and design assignments. Additionally, for ABET accreditation, all departments within the engineering school already offered capstone design courses that epitomized the idea of a culminating experience. And finally, the engineering school curriculum requires students to complete three cooperative internships, a formal mode of service learning.

With all of the primary goals of the QEP mission already addressed, most faculty members in the engineering school felt that they were already in compliance with the improvement plan, and needed to do nothing but wait patiently for their ensuing university accolades. They were not ready for more pointed questions such as, "When do you define critical thinking for your students?" and "Do you explain to your students how they are thinking critically when they do the homework problems or design assignments you give them?" For critical thinkers, the engineering educators had been remiss in applying intellectual standards to their course content and presentation.

Once the deficiencies of the current engineering curriculum with respect to the QEP objectives were identified, changes were enacted to improve the program. A variety of courses from introductory level to graduate level have been altered to include explicit mention of critical thinking and exercises in their presentation materials based on application of the Paul-Elder framework. The alterations in these courses have not focused on changes in content, but have been modifications in mode of presentation. In no course has this change in approach been more interesting than in a truly basic course, Engineering Mechanics: Statics.

Changing Statics

In 1687 Newton published his laws of motion in the *Philosophiae Naturalis Principia Mathematica*. This work ultimately became the source material that has been passed on from teacher to engineering student through Engineering Mechanics: Statics and many other subsequent courses. However, while much of the information presented in statics hasn't changed since 1687, it could be argued that the teaching methods used to convey the information have also been relatively fixed. A quick review of the available textbooks indicates the same rote presentation sequence (some books are on their 12th edition). Thus, with the impetus of the QEP, it appeared necessary to see whether overt, intentional presentation of critical thinking could be integrated into a well-established, fundamental, almost archaic engineering course. Interestingly, it was found that many of the new teaching methods being discussed can be readily adapted to statics with only minor tweaking of the course presentations. A wholesale course change was not required since most of the core teaching fundamentals were already present, but presentations were not couched in the language currently used by the learning experts.

Guidance in how to modify the Statics course to incorporate improved critical thinking by students was obtained from a number of sources. A summarization of the research indicates student performance will improve with:

- teaching strategies that require students to be active learners through involvement in groups
- practicing skills in multiple settings (in class, in groups, and through homework)
- using examples that are similar to situations the student will encounter in practice
- monitoring of student understanding and progress toward an identifiable goal
- incorporating a rationale for learning the skills emphasized in the course
- using motivational techniques (Hallet, 1984; Paul, Niewoehner, & Elder, 2001; Petress, 2009).

In order to modify the existing statics course to meet the QEP objectives, minor changes were necessary in areas of course design and grading procedures. As indicated, the changes made were not extensive, but rather only minor changes to presentation or organizational format. It is clearly understood that statics is one of the core courses within the engineering curriculum and a significant amount of information must be conveyed and mastered. Thus, the changes presented do not disrupt the normal classroom flow, but rather shift the emphasis and language to incorporate critical thinking explicitly.

Course Design

Course objective—Often the first exposure many students have to statics originates with the reading of the course description during class registration. The purpose of this description is to accurately and concisely portray the course objectives to the new student. The course description currently used at our university for statics is as follows:

> *Apply fundamental concepts of statics to examine forces, equilibrium, friction, centroids and moments of inertia, to analyze and solve engineering problems. Both vector and scalar methodologies are used.*

While the course description is technically correct, it does not convey information readily understood by the new student or generate much excitement (for the new student or the instructor). This course objective was likely written by someone very knowledgeable in the field, without consideration of its impact on the reader. A new student is unlikely to know the meaning of "fundamental concepts of statics," centroids, "moments of inertia," and equilibrium and likely only has a rudimentary understanding of forces, vectors, scalars, and friction. Thus, out of a 28-word paragraph, only the remaining 16 words are well-understood. In fact, if only the words that are well-understood by a new student are used, the paragraph is reduced to "The purpose of this course is to analyze and solve engineering problems using methodologies". Obviously, this is not a very precise course statement as it could be applied to almost any engineering course in our current curriculum!

Reading the course objectives from the students' perspective changes the entire focus of the paragraph. The previous course objective was rewritten as below to focus on learning objectives and action items.

> *Complex engineering problems can be disassembled into small components that can be solved with basic science and math skills. By asking simple questions that focus on what information we have and what information we need, we can develop simple strategies to solve many problems. Through this process the fundamental concepts of vectors, forces, equilibrium, friction, centroids and moments of inertia, may be used to analyze and solve engineering problems.*

By focusing on what we intend to do, and how we intend to accomplish it, we draw the students into the class and give them a clear understanding of the fundamental concepts presented in the class. Furthermore, emphasizing simple questions to be answered goes to the heart of critical thinking as applied in engineering. Halpern (1996) emphasizes that all critical thinking skills are involved in problem solving, including generating and selecting alternatives and evaluating those alternatives.

The first change in the Statics course presentation also calls attention to the situation in which students find themselves: required to do some difficult work—thinking. A change in disposition is required in student attitudes toward coursework. As Halpern (1996) points out, "There are large differences among cognitive tasks in the effort that is required in learning and thinking. For example, most people effortlessly learn the plot of a television sitcom they are watching, but they need to expend concerted mental effort and cognitive monitoring to learn how to analyze complex arguments or how to convert a word problem into a spatial display". Visualization is a key skill in solving statics problems.

Culminating experience—ABET accreditation requirements and recommendations from many other professional bodies have led to incorporation of a "culminating experience" into curricula for many engineering disciplines. Often, to meet ABET accreditation standards, a single capstone design class will be included in the course requirements for graduation. Could the concept of a culminating experience be of value as an educational tool in a basic course?

While the capstone design courses meet their stated objectives of providing a realistic, cross-disciplinary design experience, the benefits of the culminating experience can be adapted to a variety of courses, including statics. One of the main advantages of a culminating experience is the clear understanding of the final product or skill set. Within the statics class, it is commonplace to march through the requisite chapters in chronological order. Skills are developed in a systematic fashion, one building upon the other, until the semester ends. Where is the culminating experience? An appropriate culminating experience for statics would have to be truss design. The entire semester is devoted to building the skill set necessary to analyze the internal and external forces in any member of a truss. Thus, early in the semester it is necessary to emphasize that the test of mastery of the skills taught in this course is success in truss analysis, and everything we are doing contributes to that objective in some fashion.

Flowchart of progress—When students sit through the statics course, they are exposed to a variety of concepts ranging from equilibrium to position vectors to moments. While this material is necessarily presented in a linear fashion (Figure 1), the information does not fit together as simply as the textbook would imply. Often it appears that students have difficulty putting the current lecture materials into context, or that they lose the concept of the course objective. Thus, to help students place materials into context, a visual diagram of the course content was developed, as shown in Figure 2.

The visual diagram removes the rigid outline format and displays the systematic march of information from the first day of class through the culminating experience (i.e., trusses). A quick review of the diagram clearly indicates the reliance of the course on the understanding of fundamental vector operations. In addition, the diagram highlights the linkage between forces, moments, and equilibrium, and clearly displays equilibrium as an overarching concept to be applied to all statics problems. Defining and illustrating linkages among topics is a powerful aid to memory (Mines, King, Hood,& Wood, 1990). There are crucial relations between how information is stored and the way it is used for a given purpose. Cognitive psychologists consider meaning to be the way a concept is linked to other related concepts. A concept will have a richer meaning for a student when it has many connections to other concepts. When one concept is brought to mind, it can act as a trigger or cue for the related concepts to which it is connected. The greater the number of connections between a concept and other related concepts, the greater will be the likelihood the concept will be retained and implemented.

Grading Procedures

Defining the appropriate grading procedures for a particular course is always subject to much debate. There is not one method that will work for all courses or all instructors; thus, each must determine a solution on his or her own. However, the following grading procedures have been adapted to the statics class with reasonable results and thus warrant further review. If you deem them appropriate for your class, then we would encourage you to experiment with any or all of these options.

Pre-quiz—In today's environment (and likely throughout history) it is challenging to motivate students sufficiently so that they come to class prepared. Ideally, every student should have read the lecture material before class and be prepared to comment on the problems. However, in reality, that rarely is the case. Following the mantra that "if something is important, measure it," the statics class has been modified such that a pre-lecture quiz is given every day. This pre-quiz is based on the preparatory materials and should take no more than five minutes to complete. Students are thus rewarded for class preparation and it is deemed important to the instructor. Students also are given the chance to monitor their own progress and level of preparation. The thinking is that the time lost during the quiz should be easily made up as the class is prepared for the lecture and has a preliminary understanding of the material to be covered. The questions that are asked in the quiz also serve an important function in learning. Instead of just recalling a fact or bits

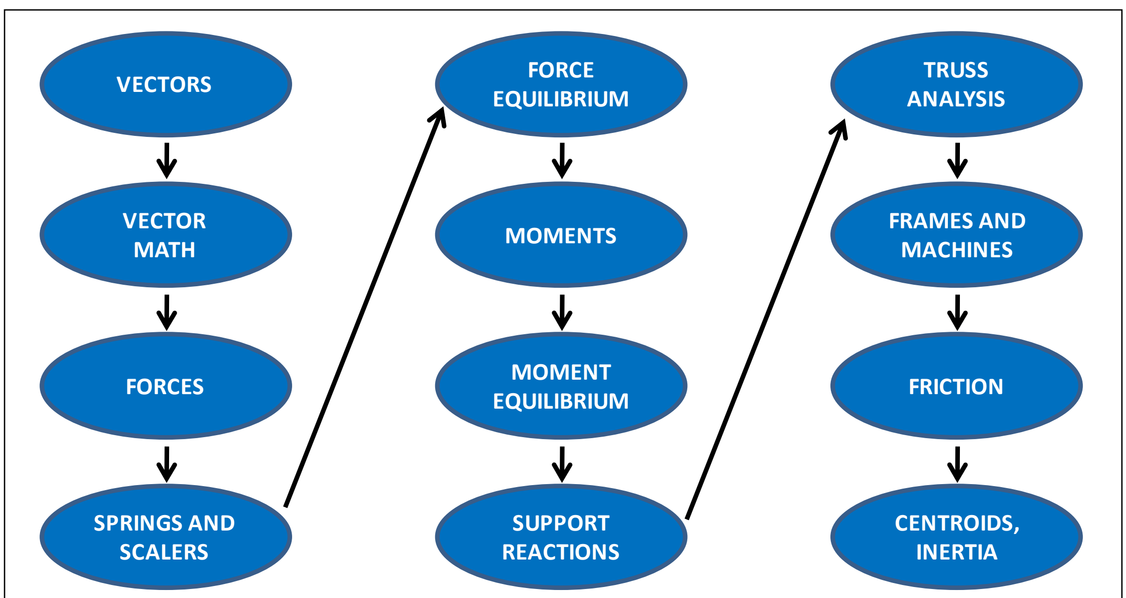

Figure 1. Traditional flow chart of information presentation within Statics.

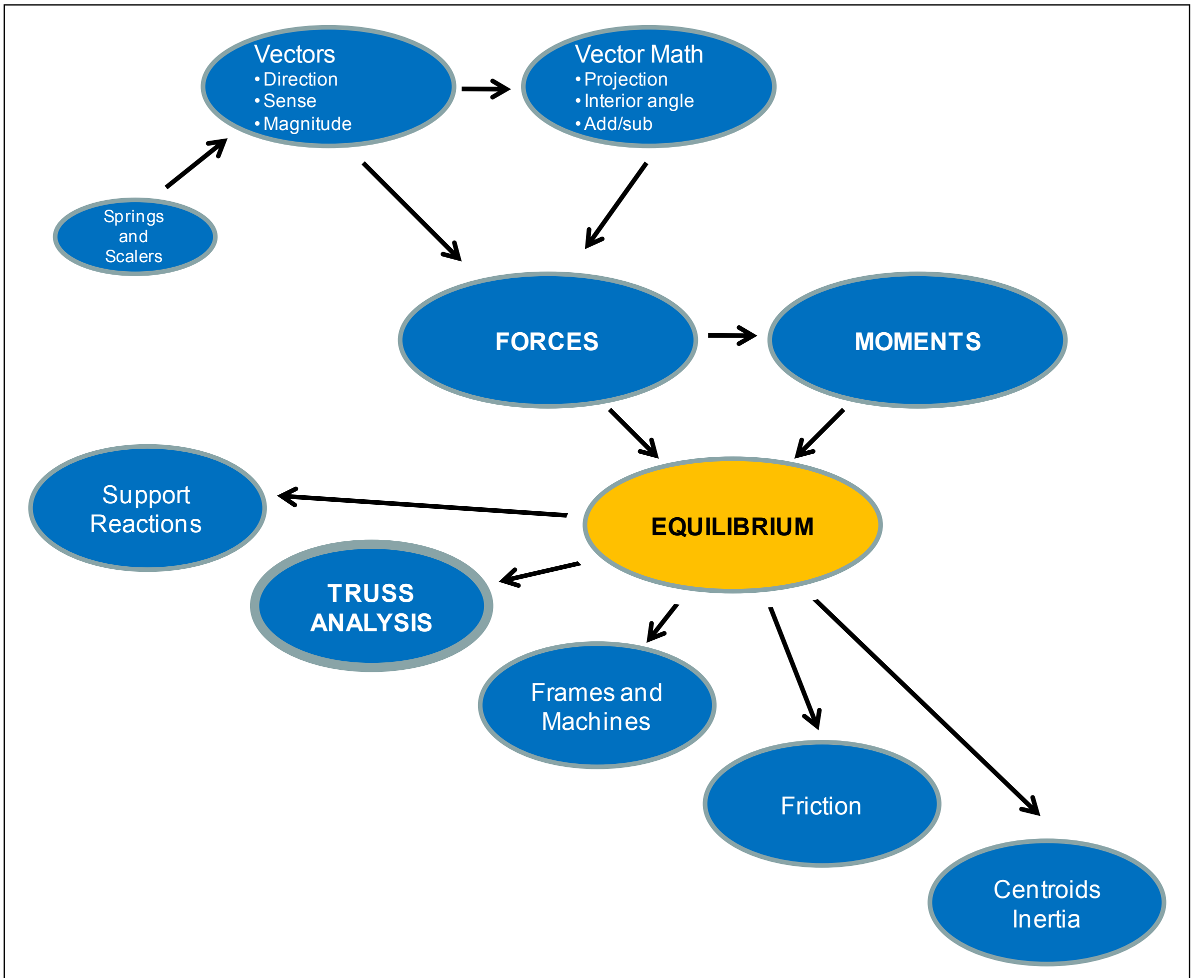

Figure 2. Modified flow chart displaying concept relationship for Statics.

of information, the thoughtful questions on the quiz require the student to consider a concept in connection with a situation reflective of actual practice when the relevant concepts allow solution of real problems.

Group problems—Much of the learning we do throughout our academic careers occurs in a group setting. Considering study groups and laboratory exercises, it is clear that we do not spend much time learning material in isolation. Group learning has the benefit of exposing students to a variety of individuals and enabling them to ask questions in a relatively safe environment. A small group in the classroom is one form of a "circle of trust" (Palmer, 2004). To help facilitate group learning, the students are generally asked to complete one homework problem that must be submitted prior to the end of class. Students are encouraged to work in small teams, but each student must submit his or her own handwritten problem for evaluation. These types of assignments force an immediate application of the presented material. Students who do not readily grasp the lecture materials are then mentored by those who do, further solidifying course materials.

Optional final—The purpose of the statics class is for students to gain a mastery of basic science and math skills such that they are able to solve simple engineering problems. It is clearly evident that some students may struggle with initial concepts, but that through repetition of material, are able to master the subject matter. However, the traditional grading format, where each test contributes a set percentage to the cumulative grade, works to disenfranchise students if they have one low test score. Suddenly, because of one poor test score, their grade is unsalvageable and they give up. In an effort to maintain student commitment, we have gone to an optional final, where the final will replace the lowest test score. This rewards the high achievers as they may choose not to take the final if they are satisfied with their performance. It also keeps other students engaged longer as they can significantly improve their class grade with the last chapter exam and a good score on the final. It is noted that students are cautioned that if they choose to take the final, their score will be included in their average, regardless of whether it helps or hurts their performance. This provision is necessary to keep students from just taking a desperate guess and turning in a poor performance (and it also reduces grading!).

Metrics for Change

When making systematic changes to a course as fundamental as statics, it is imperative that assessment tools are in place to provide metrics. Without appropriate tools it is impossible to determine whether enacted changes are beneficial or a distraction to the students. Unfortunately, class evaluations are not generally a reasonable means of measuring student outcomes, as the perception of learning often varies significantly from actual achieved learning.

Thus, to assess the effect of the modified course curriculum, data on four separate instructors covering 15 different classes and 672 students between 2004 and 2008 were compiled to first identify baseline performance (Figure 3). Rather than standard deviation, the inter quartile range (IQR) was used to measure how tightly the data is clustered around the median value such that the IQR is the minimum range required to capture half of the data. A low IQR value indicates the data values are all very close to the median value and a large value indicates the data are wide-ranging. To visualize the median and IQR concept a box plot was developed to graphically depict the values and other important information. For the composite

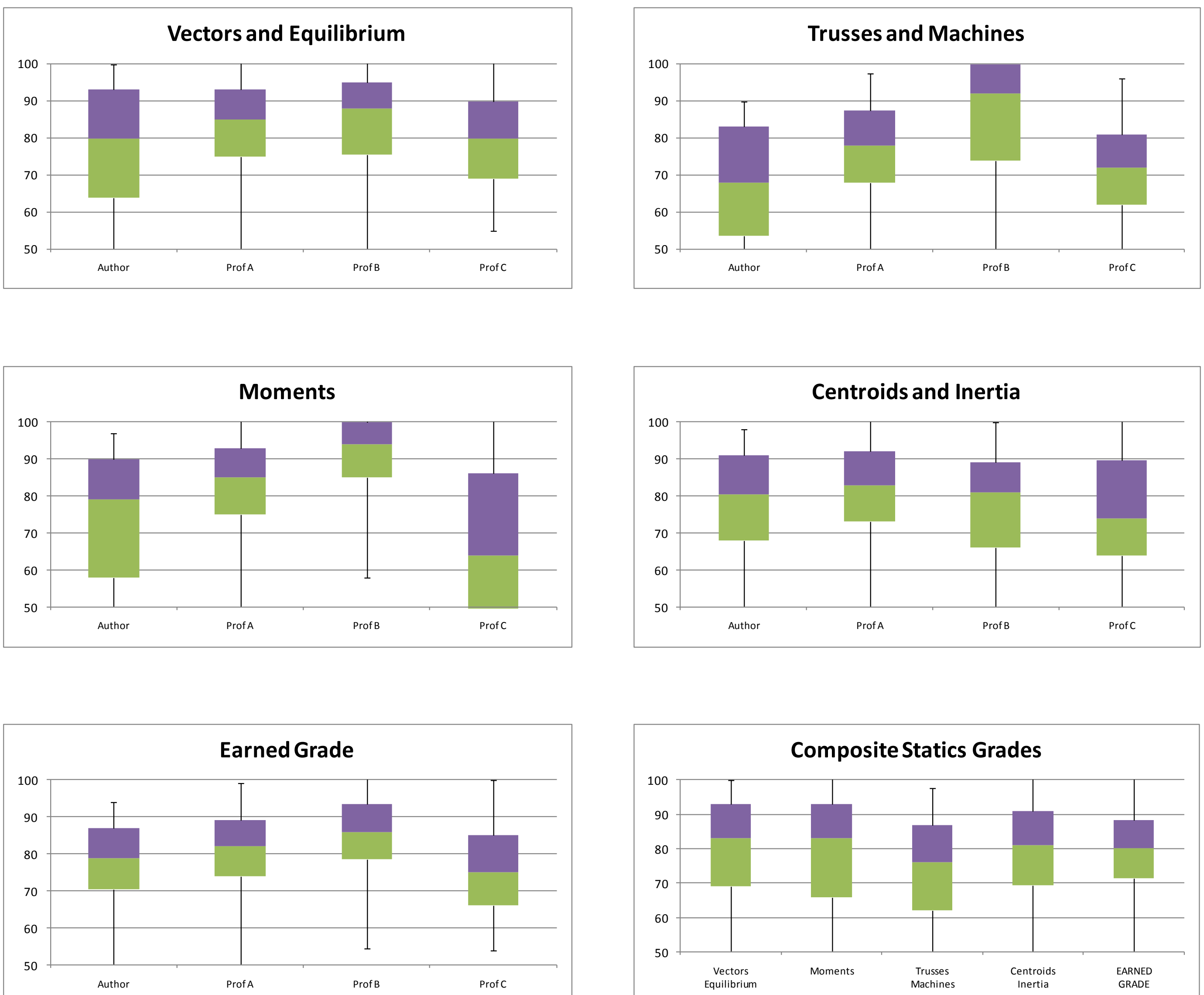

Figure 3. Baseline statistics for course materials

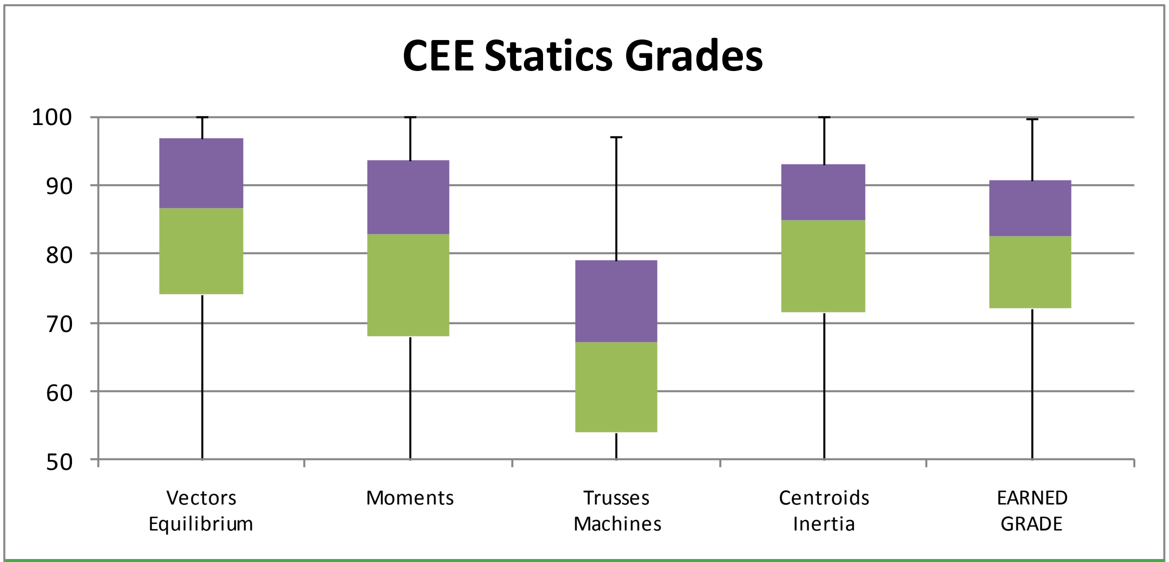

Figure 4. Statistics for modified statics materials

data, the median test average for the vector equilibrium exam was 83 and the IQR was 24. The IQR value represents a much tighter data clustering than the standard deviation (half of the data is captured within two standard deviation units, 34.8).

Using the statistics displayed in the box plots, both student and instructor performance can be quickly assessed. By reviewing the composite grades, it is evident that the "low point" in the semester for the students is associated with their understanding of trusses and machines. Interestingly, while Prof B has the highest class scores for this topic, Prof A's classes appear to have a much more uniform understanding of the material as evidenced by the low IQR.

As discussed, numerous changes were made to the statics course in an attempt to improve student performance in coordination with the university's quality enhancement plan. During the summer semester of 2009, 115 students were enrolled in this single statics session. The statistics from this class were compiled and the box plot data are presented in Figure 4. After a slight shift in the focus of the class and the incorporation of critical thinking concepts, a marked improvement in student performance was observed. From a previous median value of approximately 80, the class modifications shifted the test median to the mid to upper 80s (with the exclusion of the truss and machine test!).

The lower average on the trusses and machines test is not overly concerning as this is the students first attempt at putting together the multiple concepts. The lectures use the truss design as a general guide so that students can see applicability of their work throughout the semester. What is more critical in this case is the improvement in overall student understanding of the concepts.

Focusing more closely on "EARNED GRADE" assessment, presented in Figure 4, can also work to help assess the results of the course modifications. Figure 5 displays a comparison of the author's grades for the previous courses and for the Summer 2009 session where modifications were presented. As shown in the figure, it appears that there is a significant shift of students to higher grades. Many of the "B–C" students appear to be in the "A–B" range. Unfortunately, the "F" students appear to have benefited little from the course changes.

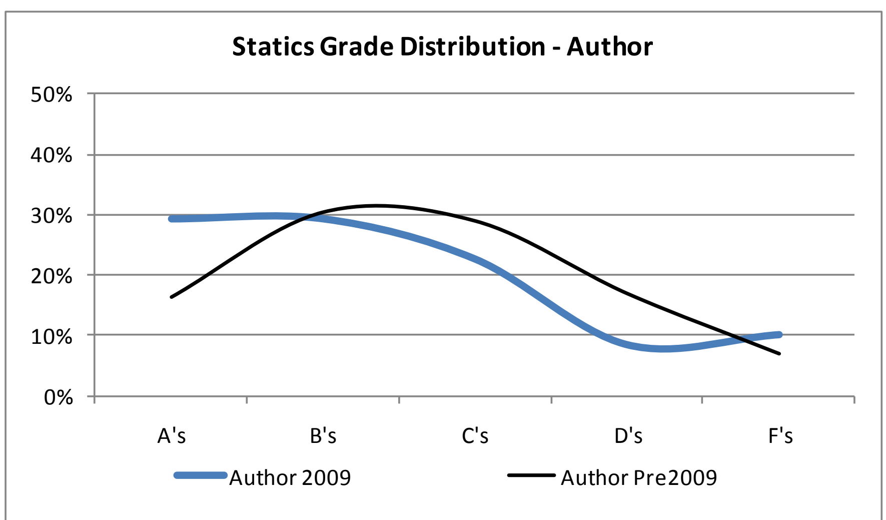

Figure 5: Course grade comparisons between modified curriculum and previous statics classes

Student Reactions

It is always challenging to gauge or quantify student reactions to course content changes. About the only mechanism available is the course evaluation form, and that obviously cannot provide a quantitative assessment. However, as the form is the only information available, it can be used to provide a general feel or qualitative assessment of student reactions.

The course evaluation was provided to the students on the last day of the summer semester, after Test 4 had been returned and discussed. Approximately 59 of the 115 students completed the questionnaire and the results are displayed in Figure 6. Questions 4, 6, and 7 were used by the University to determine the cumulative class rating as 4.45 out of 5.0. Figure 7 compares the individual responses of the questions from previous classes to those of the modified curriculum (shown by the continuous line).

The open-ended questions answered by the students also provided insightful information. Most of the comments were very positive, as summarized below:

> "Applied math and science concepts to real world engineering problems"
> "I learned"
> "A lot more interesting and fun than I expected"
> "The group quiz idea is genius. It forces students into study groups to learn the material."
> "Give the professor a raise"

The negative comments primarily focused on not working enough example problems and frequently focusing only on the initial problem setup rather than completely solving an example problem to its exact solution. This, however, is a considered decision that is made due to lack of time. In my opinion, class time is more effective helping students set up problems rather than helping them work their calculators to generate an answer.

1. Were the goals of this course established?

A.	59	98.30%	Yes (5 points)
B.	0	0%	No (0 points)
C.	1	1.70%	Somewhat (1 points)
D.	0	0%	I cannot recall (0 points)

2. Were the goals of this course met?

A.	59	98.30%	Yes (5 points)
B.	0	0%	No (1 points)
C.	1	1.70%	Somewhat (1 points)
D.	0	0%	I cannot recall (0 points)

3. To what extent have/has your knowledge and/or skills been increased as a result of taking this course?

A.	0	0%	None (1 points)
B.	8	13.60%	Somewhat (3 points)
C.	51	86.40%	A lot (5 points)

4. Rate the effectiveness of this instructor's classroom presentation (e.g., preparedness, delivery, format, use of illustrative examples, etc.).

A.	0	0%	Ineffective (1 points)
B.	0	0%	Low (3 points)
C.	2	3.40%	Average (3 points)
D.	31	52.50%	High (4 points)
E.	26	44.10%	Extremely Effective(5 points)

5. Rate this instructor's attitude toward students (e.g., availability outside of class, adequacy of office hours, adherence to scheduled class times, etc.)

A.	0	0%	Very poor (1 points)
B.	0	0%	Poor (2 points)
C.	2	3.30%	Average (3 points)
D.	10	16.70%	Good (4 points)
E.	48	80%	Excellent (5 points)

6. Rate the overall effectiveness of this course.

A.	0	0%	Ineffective (1 points)
B.	0	0%	Low (2 points)
C.	3	5.10%	Average (3 points)
D.	33	55.90%	High (4 points)
E.	23	39%	Extremely Effective (5 points)

7. Rate the overall effectiveness of this instructor.

A.	0	0%	Ineffective (1 points)
B.	0	0%	Low (2 points)
C.	1	1.70%	Average (3 points)
D.	22	37.30%	High (4 points)
E.	36	61%	Extremely Effective (5 points)

Figure 6: Class evaluation survey for modified curriculum

Conclusions

The entry level engineering course Statics was modified to emphasize critical thinking skills, identify a culminating design experience, and promote alternative learning styles. Based on the recorded student performance and comments received during the course evaluations, these minor modifications had a positive effect on student performance. Thus, improved student interaction and understanding can be achieved by repackaging course content to emphasize the goals established by the QEP. It is not always necessary to make broad sweeping changes to a course, but rather it may be

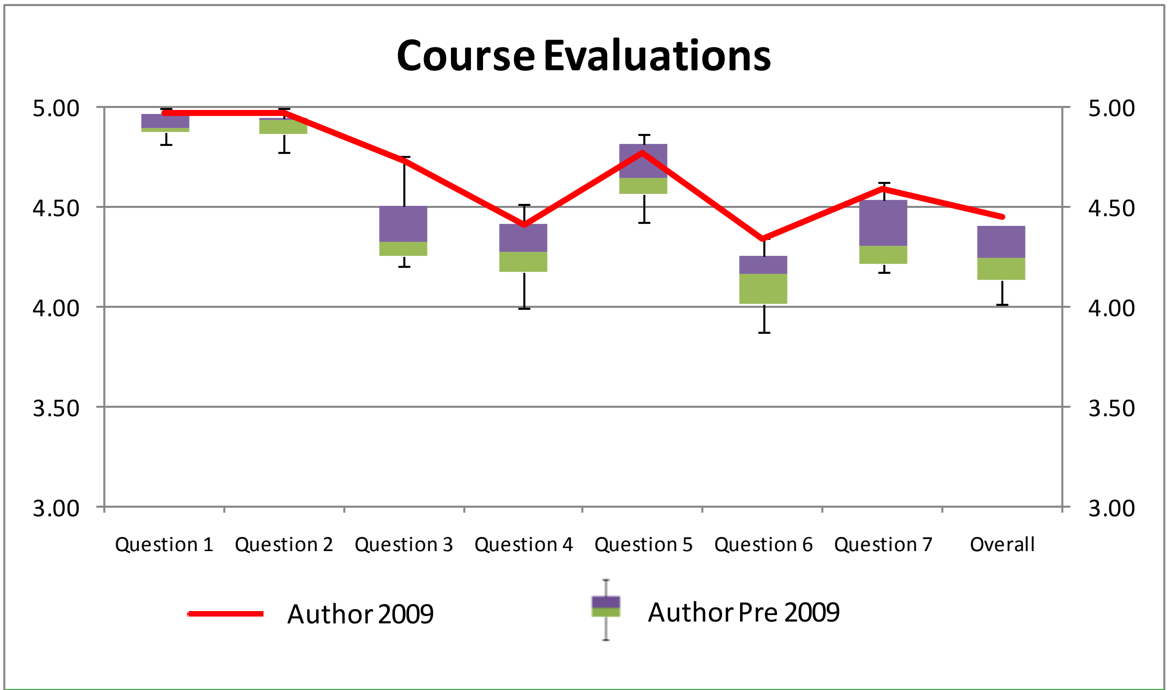

Figure 7: Student evaluation comparisons between modified curriculum and previous statics classes

beneficial to make a variety of little, incremental changes.

Another aspect of the effects of the changes made in the course is impact on instructors. The authors experienced a very positive reaction to the changes on several levels: the sine qua non of engineering, critical thinking, was reinforced in an explicit way; use of a semester-long goal (truss design) that synthesized course concepts gave the students another way they could judge their progress; and this mode of presentation was more intrinsically satisfying. Furthermore, this experience could be described as has been done in this paper, and be used to encourage colleagues to make similar changes in the courses they teach.

While the course modifications did indicate a modest change in student performance, groundbreaking revelations were not identified or observed. However, is it reasonable to expect dramatic changes in performance in a course that was already well-designed, but was modified to improve critical thinking abilities? Halpern (1996) has put this type of effort into perspective: "Courses that are designed to enhance the thinking abilities of students will usually identify a subset of skills…and design instruction to develop the selected skills… Given our knowledge of cognitive development, it would be unrealistic to expect a huge gain in the thinking abilities of college students that can be attributable to one course that is a quarter or semester in length...Cognitive growth is a gradual and cumulative process; there are no quick fixes. It is more realistic to expect modest improvement in thinking abilities…".

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