

Analysis vs. Design: Why the *Versus*?*

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It is the position of the authors that 'Analysis' and 'Design' should be taught as complementary skills rather than competing ones. Furthermore, the authors believe that the instructors of most (if not all) engineering courses should teach analysis and design skills and methodologies in a simultaneous and integrated manner. This paper outlines the efforts of the Engage program to integrate design and analysis in the freshman engineering curriculum at the University of Tennessee. Details of the curriculum structure and the process by which the integration of design and analysis is achieved are presented. Discussions of quantitative and qualitative assessment techniques and results as well as intended future initiatives are also presented.

INTRODUCTION

ANALYSIS AND DESIGN are often considered alternative and competing engineering education methodologies. This dichotomy is prevalent in the debate on engineering education reform, as evident in the proposed topic areas for this conference. Unfortunately, this dichotomy is also reinforced in the structure of the engineering curriculum, where most courses are dedicated to either analysis or design. Our contention is that analysis and design should not be considered alternative methodologies but rather as complementary skills that should be taught and applied simultaneously. This is the approach we have taken in the Engage program at the University of Tennessee. We have a common freshman year where the engineering coursework is one, 12 credit hour year-long course. In this approach, the entire Engage faculty is responsible for the development of the integrated curriculum, lesson plans, projects, and teaching approach. Often, the same professor may be presenting and discussing both analytical and design techniques in the same session. It is our position that this integration not only meets the specific requirements of EC 2000 a–k outcomes but also reflects the true intention of those outcomes, in that a well-prepared engineer must utilize a wide variety of skills and techniques in the development of problem solutions.

Attempts have been made to integrate analysis and design before, and for many years the mantra of 'Design Across the Curriculum' has been advanced as the preferred pedagogical model. However, this integration has been difficult for a number of reasons. One problem is that most courses are the province of a single professor and thus the integration requires the buy-in of most, if not all, faculty members. A second problem is the compartmentalization of the curriculum itself.

Every semester students take a collection of courses divided into three- or four-hour segments. While many of these courses will cover related and/or complementary material, each is taught in a vacuum without any attempt at correlation or integration. Traditionally, we teach science in analysis courses and application in design courses, and seldom do we do anything but express frustration when students can not transfer knowledge from one situation to another. The Engage program has overcome many of these obstacles and is effective in the integration of analysis and design and the development of better problem-solvers. The key to this improvement comes from improving the students' ability to transfer skills through the integrated program.

The Engage program is a 12 credit hour year-long course that replaced five separate courses composed of 13 credit hours taken at a student's own pace and scheduling arrangement. The central objective in the development of Engage was to continue to teach essential skills, using techniques that improve problem-solving ability, teach design methodology, and teach teamwork and communication skills. The traditional subject matter addressed in this course is mechanics physics through statics and particle dynamics sufficient for the Fundamentals of Engineering exam, computer programming with Matlab, and visualization and computer graphics with Mechanical Desktop. Team projects are a continuous course component with a project always being worked that requires the use of the instructed mechanics physics, design, computer programming and visualization.

Engage is a large-scale implementation of an integrated curriculum. Students completing the freshman year of engineering at UT have no other option. The Engage program was piloted during the 1997–98 academic year with 60 students. In 1998–99, the program was scaled up to 150 students, and it was fully implemented with the entire freshman class of 465 students during the

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1999–2000 academic year. The program, now known as the Jerry E. Stoneking *Engage* program, is in its sixth year of operation and is taught to approximately 500 students a year. We teach approximately 4500 student class hours per week with a teaching team consisting of six faculty, 24 graduate teaching assistants, and eight undergraduate assistants.

The obvious question becomes: *Is the Engage program successful?* Based on a number of quantitative measures, the program is successful. Specific measurable results include increasing freshman retention by 15%, statistically significant grade increases in departmental follow-on courses, and increasing on-time graduation rates in engineering by 10–15%. Students are matriculating at a faster rate, most likely due to the influence of the pace of the lock-step freshman year. Based on these numbers, we certainly are producing more engineers and they are performing better in their academic career. *But are they better problem-solvers?* We are currently in the process of trying to answer this question. We are using qualitative analysis techniques in interviews of engineering upperclassmen to get detailed feedback on their understanding of the problem-solving process and the major curriculum contributors to that process.

In this paper, we provide details of our integrated curriculum, particularly: how we integrate design and analysis and teach transfer of skills; our assessment techniques and the results; and proposals for how our model may be extended beyond first-year coursework.

OVERVIEW OF THE ENGAGE CURRICULUM

Details of the Engage program's development, structure, history, and successes have been published previously [1, 2]. A brief summary of the previously published program description is presented for continuity and clarity.

The Engage curriculum consists of two integrated, *team-taught*, six credit hour courses in Engineering Fundamentals (EF). EF 101 (which is only taught in the fall) concentrates on teaching basic computer programming, graphics skills, and problem-solving in the context of a non-calculus based introductory statics and dynamics science component. EF 102 (which is taught only in the spring) concentrates on teaching calculus-based statics and dynamics.

One of the keys to our success is our team teaching structure. The Engage teaching team consists of six faculty members, 24 graduate teaching assistants (GTAs) and eight undergraduate teaching assistants (UGAs). All faculty members in Engage have taught both analysis and design courses and/or have extensive experience as practicing engineers. The faculty is responsible for all curriculum development, assignments, and administration of the course. The GTAs assist in the

delivery of instructional material and in grading. UGAs monitor and administer the project work area.

The basic building block of the curriculum for both EF 101 and EF 102 is the instructional cycle. Each cycle starts with a one-hour lecture in a large classroom format (~150 students) taught by an EF faculty member. The lecture presents the new basic mechanics concepts of that cycle. Two faculty members have as their primary responsibility the development and delivery of all lectures. On a given day, one professor will present the same lecture to all sections of the course. The two sciences lecturers will 'swap' the lecture presentation responsibility as the semester progresses. In order to maintain integration and continuity, all faculty and GTAs attend the science lectures.

The mechanics concepts are then reinforced by a physical homework laboratory (PH) exercise, where students work in small groups under the guidance of a GTA. They will spend an hour developing and demonstrating an understanding of the basic mechanics concepts through a series of 'hands-on' exercises. One faculty member is responsible for the development of all PH exercises; however, the two mechanics lecturers will provide input into the development of all PH exercises. The responsible faculty member will also meet with all GTAs involved in PH for about two hours per week to step through the exercises, discuss objectives, etc.

The cycle continues with an analysis and skills (A&S) session, in which 30 students meet with a team of two GTAs for a 75-minute session. In EF 101, this recitation-style session teaches mathematical, computer, and graphical skills that can help the students effectively apply the concepts they have just learned in lecture. In EF 102, more of the recitation time is devoted to team and individual problem-solving, instead of computer skill instruction. Two faculty members are responsible for the development of all A&S materials. This includes lesson plans, class notes, examples of problems, homework, and supplemental material. Input from other faculty members is provided on a regular basis. The two responsible faculty members also meet with all GTAs involved in A&S for approximately two hours per week to review the lesson plans, step through the in-class examples, discuss objectives, etc.

All the material is integrated around design, build, and test team projects. The students are divided into groups of five members for the semester. They are assigned team projects that complement the material being taught in the other components of the course. Two faculty members are responsible for the development of all team projects. This includes project descriptions, in-class presentations, coordination of project testing, and report grading. Input from other faculty members is provided on a regular basis. The two responsible faculty members will meet with all GTAs and UGAs involved in team

projects for approximately one hour per week to review the current status of all projects. Details of the design/team component of the course and how it integrates synthesis and analysis are provided in the next section.

There are typically two cycles per week and four to six cycles per 'module.' Each module ends with an in-class exam. The students spend nine hours a week in class for each of the six credit hour classes.

INTEGRATION OF DESIGN AND ANALYSIS

Design is introduced into the curriculum through the use of team projects. There are four team projects in EF 101 and two in EF 102. The difficulty of the projects increases and the objectives evolve and are reinforced as the year progresses.

The first two projects in EF 101 involve an estimation exercise and a mechanical dissection. The goals are for the students to learn that design is a natural process closely related to problem-solving skills they already possess, to experience success as a designer, to have a positive team learning experience, and learn that design success is fun and somewhat compensates for the rigor of engineering study. The message to the students is that they already know how to solve significant problems, and we are there to show them how to organize their efforts and to teach tools that they can use to increase their problem-solving abilities.

The final two projects of EF 101 involve constructing a device out of simple materials and testing of the devices. These two projects are loosely tied to the topics being discussed in the other sections of the course, providing real objects to be drawn in graphics and practical examples of the technical material being presented. For example, the design and construction of a foam-core chair complements the discussion of free body diagrams and pre-statics. Objectives for these two projects include practice in oral and written report formats, team roles, project planning, appropriate problem specifications, background searching, and idea generation and selection.

As the EF 101 semester progresses, elements of a design method are formally introduced and practiced as the projects become more difficult. These elements are introduced both in the team/project component of the course as well as the lecture component. For first-year students, our experience has been that the appropriate design methodology must be very simple and intuitive and must correlate with problem-solving methods they have used before. A specific example is the Pugh chart [3], which is introduced as a concept selection technique. We introduce this method as a convenient way of assigning numbers and formalizing advantage-disadvantage lists, which is the same principle they have all used informally for making decisions. For overall methodology, we use a variation on the

problem-solving methods discussed in Lumsdaine [4] and Fogler [5].

In EF 102, only two design problems are assigned, giving the students time to integrate what they have learned about design, and step through the process for each project. Additional requirements that are introduced are the use of concept selection techniques, performing basic experiments on the concepts generated or materials used, and predicting the performance of their device before testing. Matching the technical content of the course, the first project is static, typically a structure design where they can perform a predictive truss analysis, and the second project is dynamic, where their new knowledge of programming is utilized by requiring a predictive program for a device with changeable inputs. We have used bungee egg drops and several variations on a catapult theme (field goal kicker, shooting at a moving mouse, etc.) for the dynamics project.

As analysis topics are introduced in the mechanics lecture portion of the course, examples are often selected and discussions are presented that illustrate how these techniques can be applied to the current design project. The techniques are introduced at the most advantageous time in the project schedule. For example, specific truss analysis techniques are introduced about two weeks after the static bridge project is assigned. This allows the students time to do some background study on existing bridge design and to begin generating ideas for their solution without worrying about all the details. After they have generated a sufficient number of design ideas and have a qualitative understanding of bridge design, they are ready to make quantitative evaluations and begin the idea selection process. Introduction of truss analysis at this point has the greatest impact, since the students can immediately see the usefulness and application of the technique. This coordination of the introduction of various analysis techniques at key points in the project schedule is possible because of Engage's team-teaching approach.

In this manner students learn to use the various analysis techniques as tools in their synthesis process. That is, as they generate solution ideas for their projects they have the necessary tools to quickly assess the merits and pitfalls of each alternative. Understanding why one design is better than another from an engineering analysis point of view allows the students to generate new solution ideas that will produce even better results. Students are able to *transfer* the various mechanics concepts and analysis techniques usually presented in the context of a closed problem to the solution of an open problem (i.e. their projects).

ASSESSMENT

The Engage program was piloted during the 1997-98 academic year with 60 students. In

Table 1. Performance on common statics final

	Fall 1997		Fall 1998	
	Pilot	Control	Transition	Control
No Errors	44	37	50	36
Common Errors	71	57	69	52

1998–99, the program was scaled up to 150 students and it was fully implemented with the entire freshman class of 465 students during the 1999–2000 academic year. During the pilot year (1997–98) and the transition year (1998–1999), the Engage program and the traditional program it replaced were run in parallel. This allowed us to conduct several quantitative studies to assess the effectiveness of the Engage program. Details of the demographics, statistical methods, and results of these studies have been discussed in Parsons *et al.* [1], but some of the significant results are repeated here for continuity.

To compare academic performance between Engage and traditional students, common finals in statics and dynamics were given to both groups in the pilot and transition years. The exams were multiple choice with up to ten different answers for each problem. Possible answers included results of common errors. These answer choices included typical errors such as sign errors and common incorrect assumptions. The Engage students had a potential disadvantage with these exams compared to traditional students in that they took both the statics and dynamics exams within a few days of each other. Engage covers both topics in EF 102 (statics first), while traditional students normally took either statics or dynamics for the semester.

Table 1 summarizes the four groups' performance on the statics final. Even though it had been approximately seven weeks since the Engage students had covered statics, they consistently did better than the traditional students. The 'No Errors' entry is the average for all questions of the percent of students who got a given problem completely correct. The 'Common Errors' entry is a similar average for students who made a simple error on the problem that resulted in an incorrect answer. This number mirrors the awarding of partial credit that is common on engineering exams. In both years, the Engage students did considerably better than the traditional students.

Similar results for the dynamics final are presented in Table 2. The *Engage* students again performed better than the traditional students.

Table 2. Performance on common dynamics final

	Fall 1997		Fall 1998	
	Pilot	Control	Transition	Control
No errors	45	37	45	36
Common Errors	65	58	59	60

Table 3. Average course grade in first departmental engineering courses

Course	Fall 1997 Freshmen		Fall 1998 Freshmen	
	Engage	Control	Engage	Control
Civil Engr 210	—	—	3.38	3.06
Chem Engr 200	3.50	2.82	3.42	2.75
Elec Engr 301	2.50	2.12	2.73	1.85
Engr Sci 231	3.00	2.72	2.70	2.34
Mech Engr 331	2.79	2.47	2.78	2.32
Indus Engr 201	—	—	3.17	2.75
Matl Sci 201	3.09	2.75	2.66	2.34
Nuc Engr 203	2.88	2.63	3.18	2.74

All differences are significant at a 95% confidence level.
 — = One Engage student in the course.

Another measure of the success of the Engage program is student performance in their first departmental course (usually taken in the fall semester following the completion of EF 102). This comparison is shown in Table 3. In all cases Engage students did better, and, in some cases, much better, than their counterparts with the traditional freshman preparation.

Based on the data, it is easy to argue that the students who went through the Engage program are better problem-solvers, at least on *closed* or analysis-type problems (i.e. the typical type of exam problem used in all the courses listed in Tables 1–3). We attribute this increased performance to the integration of the curriculum, particularly the integration and simultaneous teaching of design and analysis. The Engage students simply see more problems and a wider variety of problems.

Assessment of an improvement in the ability to solve *open* or design-type problems is more difficult to ascertain, particularly in a quantitative manner. A number of qualitative assessments have been made or are underway and preliminary results are reported here. A more thorough discussion of all these qualitative assessment techniques and their results will be presented in the near future.

The Engineering Fundamentals Liaison Committee is a committee that serves as a conduit between the Engage program and all the departments in the college. This committee is composed of a representative from every department, the Director of the Engage Program, and one of the Associate Deans (Committee Chair). One of the charges of this committee is to develop assessment techniques that would contribute to departmental ABET packages, with a priority given to those ABET a–k issues most needed by the departments. The priorities were outcomes 'c' (design), 'd' (teaming), 'g' (communication skills), and 'k' (techniques, skills, and modern tools). The Liaison Committee has developed an assessment plan for these items that will proceed along three tracks.

Table 4. Responses to the Engage on-line survey

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
My experience in EF 101 and EF 102 has improved my understanding and ability to work in teams.	3%	7%	21%	45%	24%
My experience in EF 101 and EF 102 has improved my ability to design a device that meets a desired need.	1%	3%	12%	50%	33%

Track 1

Track 1 involves the development of a student self-assessment questionnaire to be completed at the end of EF 102. These survey items would cover the four ABET items requested by the committee. Each question requires the student to rate his/her improvement in that objective on a numerical scale. For the 2002–2003 academic year, the results for the two questions that are related to teaming/design are presented in Table 4.

Table 4 indicates that an overwhelming majority of the students feel that the Engage experience has improved their ability to work in teams and to succeed in the engineering design process. Obviously, the perspective of the students is limited, due to their limited experiences in engineering; however, the fact that students have gained an appreciation for design experiences and its importance in their future success is encouraging. This survey will be repeated every year and the results will become part of every departmental ABET package.

Track 2

While the freshman survey gives useful information, all of these ABET criteria address complex learning situations that are notoriously difficult to teach and assess. Therefore, we also performed a qualitative study of upperclassmen that consisted of in-depth interviews of representative students in the college. Transcripts of the interviews will be analyzed for themes of how students develop the skills contained in these priority items. This will provide direction for how we really help our students learn the skills they need, and what kind of assessment would be the most effective in the future. We have the expertise to perform this study with two trained interviewers (counseling psychology Ph.D. students). The first of these interviews was conducted during the spring of 2003.

Participants were recruited from a pool of senior engineering students suggested by engineering faculty members as *representative* of engineering students in their respective departments. The suggested names constituted a pool of potential participants from which actual participants were to be randomly selected and invited to participate. Of the 29 students suggested by faculty members, 11 were removed from consideration because they had no experience with the Engage program. The remaining 18 students were invited to participate and 8 students ultimately agreed to be interviewed. Participants represented six engineering

departments. Participation in this study was strictly voluntary, with no class credit or other inducement provided.

All interviews were conducted in the investigator's office or conference area. Participants were informed of the confidential nature of the study and asked to sign consent forms before interviewing began. The confidential audiotaped interviews usually lasted 45–50 minutes. The co-investigator used an open-ended semi-structured interview format to interview participants. Interviews were conducted using both audiotape and written notes to collect data. Participants were allowed to stop the interview or audiotaping at any time and could exclude data as they wished, though no participant chose to do so. Audiotapes of the interviews were professionally transcribed for analysis. In each case, the interviewer began by asking the student to self-assess themselves in each of the priority areas, and then to describe their experience with that area. The idea was to let the student describe how they believe they have learned these skills.

Detailed analysis of all transcripts and data is ongoing and only *very* preliminary findings are reported here. Overall, these participants reported a positive experience with Engage. They liked the early introduction to team experiences in engineering, from both a task (exposure to design) and a relational perspective (development of teaming and communication skills). For example, several participants identified the benefit of a 'hands-on' experience, while most participants also identified the benefit of having to 'work with people different from you.'

Track 3

Engage is in the middle of a longitudinal study of teaming skills and attitudes. In 2002 and in 2003, students in senior design in seven different majors were asked about their teaming skills and attitudes. The survey consisted of 33 questions for which the students rated their response from 1 (strongly disagree) to 5 (strongly agree). The survey included students who went through the Engage program as well as those who went through the traditional program that was replaced by Engage in 1999.

Again, detailed analysis of the data is ongoing and only *very* preliminary findings are reported here. Generally, the results support a relationship between students' attitudes about teams and their engineering discipline, course enrollment, and overall satisfaction with the engineering program.

Our data suggests that students in Mechanical Engineering (ME), Biomedical Engineering (BE), and Electrical Engineering (EE) have had a more positive experience with teams while at the University of Tennessee and may be more likely to pursue future team experiences than their cohorts in other programs. Students from the ME and EE programs were also more likely to express a desire for more team-based experiences. A variance in student attitudes about teams was also associated with their course enrollment. Our preliminary analysis suggests that students in ME 479 (Capstone Design) may have the most positive attitudes about teams.

We also found evidence of improvement in team attitude associated with team-based training. Students who received team-based educational experiences (Engage) were more likely than their traditionally trained cohorts to affirm the value of teams for enhanced learning. Students with extended team-based training (i.e. participation on our Engineering Communications minor program) expressed greater appreciation than traditional cohorts of the opportunity to work on teams as part of their engineering education. When compared with a composite of traditional and team-based cohorts, students with extended team training were more affirming of both the value of teams for learning and the opportunity to be involved with them. Together, these findings support the contribution of our team-based learning experiences to the fulfillment of ABET objectives regarding the equipping of students to function effectively on teams.

FUTURE INITIATIVES

The Engage course delivery structure is not only effective but also efficient, with a cost per student credit hour about one-third the college average.

Effectiveness and efficiency are both reasons to extend the Engage model beyond the freshman year, especially to areas of the curriculum shared by students from different departments. 'Service' courses such as Rigid Body Dynamics, Thermodynamics, and Circuits, or a senior level introduction to design course are being considered at this time. Our intention is to develop a plan this coming academic year and then to pilot one or more of these courses in the 2004–2005 academic year. Currently, the Engage faculty is participating in a department-level curriculum redesign with the Civil and Environmental Engineering Department. This work is underway and will proceed over the next few years.

CONCLUSIONS

Design and analysis are often considered to be competing engineering education methodologies and debates are common as to which one should be emphasized. It is the belief of the Engage program that engineers require both design and analysis skills in order to be effective problem-solvers and that design and analysis should be taught in a complementary and simultaneous manner.

The structure and implementation of the Engage curriculum accomplishes this goal. Our system works because the faculty integrates and team-teaches the entire curriculum. No particular section or single component of the class is under the direct control of a single faculty member. All faculty are involved to some extent in all aspects of the class, including those that entail analysis and those that entail design.

Now that the Engage curriculum and structure is well established and shown to be successful, work is ongoing to extend the model beyond the freshman year.

REFERENCES

1. J. R. Parsons, J. E. Seat, R. M. Bennett, J. H. Forrester, F. T. Gilliam, C. D. Pionke, D. R. Ramam, T. H. Scott, W. R. Schleiter, F. E. Weber and D. C. Yoder, The Engage program: Developing, implementing, and assessing a new first year experience at the University of Tennessee, *International Journal of Engineering Education*, **91**(4) (2002) pp. 441–446.
2. C. D. Pionke, J. R. Parsons, J. E. Seat, F. E. Weber and D. C. Yoder, Balancing capability, enthusiasm, and methodology in a freshman design program, *International Journal of Engineering Education*, **17**(4) (2001) pp. 381–385.
3. S. Pugh, *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley (1991).
4. H. S. Fogler and S. E. LeBlanc, *Strategies for Creative Problem Solving*, Prentice-Hall, Englewood Cliffs, NJ (1995).
5. E. Lumsdaine and M. Lumsdaine, *Creative Problem Solving*, McGraw-Hill (1995).

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