A Multidisciplinary Approach to Introductory Engineering Design

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Abstract - Bachelor of Engineering students at Dartmouth College are required to complete Engineering Sciences 21: Introduction to Engineering, an introductory course that teaches a systematic, broadly applicable methodology for creative problem solving. During the 46 years that the course has been offered, Dartmouth engineers consider ES21 to be a career-changing experience in their education. Consistent with Dartmouth’s liberal arts DNA, the course centers around a multidisciplinary project experience that requires integrative thinking in solving problems and that forces students to work outside their knowledge base. Working in groups of 4-5, students conceive, design and fabricate original prototype devices that address the needs of their chosen users. This experience teaches students how to bring engineering methods to bear on the solution of a societal problem. Evaluating and appropriately acting upon ethical issues that influence the engineering process, and exercising effective communication skills through development of written and oral reports are also essential parts of the course. Each group is required to estimate the production costs of their solution and develop a basic business plan for producing and marketing their product.

Index Terms – Design, Engineering Science, Group projects, Introduction to Engineering

INTRODUCTION

“ES 21: Introduction to Engineering,” an introductory design course at the Thayer School of Engineering at Dartmouth College, is an immersion into the arena of engineering innovation and technical entrepreneurship.

Thayer School has a non-departmentalized structure, which connects faculty in all areas of engineering as prospective consultants to students in the course. Depending on the needs of the design project, students may need to learn elements of digital electronics, solid and fluid mechanics, thermal dynamics, control theory, biotechnology, chemical, environmental engineering, etc. If this challenge sometimes seems daunting to sophomore-level students, it is. For the students, part of the excitement of ES21 is the high level of adrenaline from “jumping into the deep end with the course instructor often in the role of “life-guard”.

ES21 is the entry to Dartmouth’s Bachelor of Arts (A.B.) degree for Engineering majors and is also required for the ABET-accredited Bachelor of Engineering (B.E.) degree. The prerequisites to the A.B. degree are three Mathematics courses, two Physics courses, one Chemistry course and one Computer Science course. The degree has a common required core of three courses:

• Introduction to Engineering
• Systems
• Distributed Systems and Fields

All three of these courses emphasize aspects that are common to many areas of engineering. The systems courses demonstrate and provide practice in ordinary and partial differential equations to solve problems in electrical, mechanical, materials engineering etc. with an emphasis on the commonality of the mathematics.

Students are also required to take two courses from a distributive core of four courses:

• Science of Materials
• Introduction to Thermodynamics
• Control Theory
• Discrete and Probabilistic Systems

In addition, students are required to take two of seven gateway courses from different disciplines:

• Digital Electronics, or Electronics: Introduction to Linear and Digital Circuits
• Solid Mechanics, or Fluid Dynamics
• Biotechnology and Biochemical Engineering, or Chemical Engineering
• Introduction to Environmental Engineering

The A.B. is completed with two further electives and the Culminating Experience, which is either a project resulting in a thesis or a designated advanced level course with significant design content normally taken during the senior year.

The transition from the A.B. degree to the B.E. degree is seamless. Although the A.B./B.E. sequence is designed as a five-year program, about twenty percent of Engineering students are able to complete both A.B. and B.E. degrees in four years.

To complete the B.E., students take an additional nine courses, one of which is an applied mathematics course chosen from Numerical Methods in Computation, or Fourier
Transforms and Complex Variables, or Statistical Methods in Engineering.

A two-term design sequence, “Engineering Design Methodology and project initiation” and “Engineering Design Methodology and project completion”, is also required. This sequence builds on the undergraduate introductory design course. Finally, six more courses in engineering are required with at least three in a single engineering concentration. It is worth noting that the requirements for the A.B./B.E. program exceed ABET’s minimum requirements for an accredited degree.

With this prologue, we now discuss the foundation course “ES 21: Introduction to Engineering” in more detail.

**THE COURSE: INTRODUCTION TO ENGINEERING**

**I. Objectives**

The objectives for the Introduction to Engineering course include:

- Identify a social need, determine the magnitude of the problem and quantify the specifications for a solution that include technical, ethical, environmental, legal, and other requirements.
- Use engineering problem solving methods to generate a set of alternative solutions; use a matrix analysis to select the alternative that appears most viable; then design a component, system, or process to implement the alternative.
- Apply science and mathematics to describe the problem, analyze potential solutions and evaluate the final design.
- Design and conduct experiments to assess the viability of a proposed solution, and analyze and interpret the resulting data;
- Use modern engineering tools, such as Pro/Engineer or SolidWorks, in the design process.
- Work effectively on a multidisciplinary team and negotiate group dynamics
- Evaluate and appropriately act upon ethical issues that influence the engineering process.
- Communicate effectively through written and verbal reports and improve oral presentation skills.
- Begin the practice of life-long learning through an analysis of new technology.

**II. Approach**

To achieve the above objectives, students work in groups of 4-5 on a term-long design project. The specific subject of the project changes each time the course is taught. The scenario for the course is that a fictional foundation, The Dartmouth College Educational Foundation (DCEF), has sent out a request for proposals (RFP) to which each student team must respond. An example RFP on “Energy Efficiency and Conservation” is reproduced below:

Energy has become more expensive and the potential for disruption and impact on the global climate provide an impetus for more thoughtful and clever use of all sources. Viable areas for projects that improve efficiency include: transportation systems, homes and home appliances and new fuel-efficient technologies to replace old and wasteful systems. Organic farming techniques may reduce the need for fertilizers that require energy to produce. New processes for cleaning dishes and clothes could reduce the energy required to heat water. To the extent that products used in a community can be manufactured nearby from local materials there is a potential to reduce the energy required for transportation. Improved technologies for communications have the potential to reduce the need to travel to carry out business.
Energy uses in the home include: lighting, heating, cooking, cleaning and bathing. Manufacturing, farming, transportation etc all have a wide variety of energy consuming equipment. In addition, all of these devices are made from materials that need to be mined, machined, finished, packaged and transported. Improvements in any of these areas have the potential to reduce the energy required by individuals on any given day.

DCEF requests proposals for the development of ingenious and innovative systems, devices, and materials to improve the efficiency of energy usage, including advances leading to reduction in the environmental impact of energy usage.

III. Deliverables

A number of deliverables are required during the term, and each group is expected to:

- Select a problem in the field specified by the RFP.

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>GROUP #</th>
<th>REVIEWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem Statement, Customer Profile</td>
<td>Roughly defined problem, poor or no description of customer</td>
<td>Reasonably well defined problem &amp; description of the customer but little data or insight provided</td>
</tr>
<tr>
<td>Proposed Solution</td>
<td>Vague description given</td>
<td>Description given but drawings are shown</td>
</tr>
<tr>
<td>Key Specifications</td>
<td>Some general specifications</td>
<td>Some specifications given w/ vague justification</td>
</tr>
<tr>
<td>Experimentation</td>
<td>Little testing</td>
<td>Some vague quantitative data</td>
</tr>
<tr>
<td>Theoretical Analysis (equations describing the performance)</td>
<td>Little analysis - no equation</td>
<td>Some vague, qualitative analysis and an equation given but not used</td>
</tr>
<tr>
<td>Environmental Analysis</td>
<td>Little Analysis</td>
<td>Some vague quantitative analysis</td>
</tr>
<tr>
<td>Program of Investigation &amp; Timeline</td>
<td>No timeline</td>
<td>Minimal timeline</td>
</tr>
<tr>
<td>Preparation, AV aids</td>
<td>Inadequate presentation, no useful AV aids</td>
<td>Complete presentation but lacking clarity, organization and AV</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Sample ES21 Evaluation Form used by the Review Board for Progress Report presentations
IV. Assessment

A Review Board assesses and evaluates each group’s efforts. The Review Board consists of the course director, four-seven other people whose expertise cover a range of engineering disciplines, and, normally, the Director of Thayer School’s machine design and fabrication facility. The Review Board meets four times during the term to evaluate group presentations. These presentations include: a proposal for the group’s project, two progress reports, and a final presentation. Each member of the team must demonstrate presentation skills by leading at least one of these presentations. The Review Board challenges each team’s assumptions, evaluates its progress, and provides constructive feedback on direction and presentation. The grades for these presentations are the average of the individual Review Board members’ grades. The course director grades the written proposal, progress reports and the final report. A typical grading rubric, which is available for the students in advance of their presentations or submission of their written reports, is shown in Table 1.

V. Logistics

Some teams self-select. The remaining students are assigned by the course director according to their diversity of interests, experience and gender. The selection process is aided by a class event introducing Interactive Dynamics -- speed-dating style -- and a pizza dinner. The aim of these events is for students to get to know each other.

A teaching assistant (TA), who has previously taken the course, is assigned to mentor each group. The TAs are one of the keys to the success of this course. Their role is to act as facilitators for group discussions and to help students identify the resources needed for a successful outcome.

Another key to the success of the course is the extensive department resources available to the students. Each team has a $500 budget for purchasing materials that will advance their project. Physical resources include a large engineering design studio, CAD lab, full machine shop with CAD/CAM and rapid-prototyping facilities, and an electronics fabrication facility. Learning resources include the expertise of all the faculty and technical staff who provide expert advice and guidance for ES21 projects.

About two weeks into the term, each group presents a project proposal, both written and oral to the Review Board. As a variant, one course director requires a white paper in the second week, followed by a formal project proposal in the third week. While students are formulating their proposals, the course director and selected faculty give a series of lectures designed to help the students develop a successful project. These include: need finding; use of matrices for design decisions, segmentation and problem solving techniques, and how to select a problem; search techniques on the literature, markets and patents; how to give an oral presentation; and, finally, a question and answer session about the proposal, including how to structure the written and oral presentations. Two essential strategies are emphasized in these early lectures: a) developing a good problem statement is essential to solving a problem; and b) using an iterative design process is key to success, as illustrated in Figure 1.

A sample exercise of this methodology may be found in Figures 2, 3 below. Figure 2 begins with the hypothetical problem statement: “The Connecticut River is polluted and needs to be cleaned up.” The case study explores biased questions and the need to redefine problems with neutral language that do not contain implied solutions. Figure 3 diagrams the iterative process of brainstorming a solution to the Connecticut River problem using the ES21 methodology, working around the diagram from redefining the problem, to determining specifications, to brainstorming alternatives, to selecting most feasible alternatives.

The course instructor reviews the proposals with the class after the presentations. The presentations themselves are videotaped and the students are encouraged to view them with their TA in order to improve their presentation skills.

Two progress reports are required at two-week intervals after the proposal presentations. These are interspersed with timely lectures to provide useful information for the students, including lectures on: models, mock-ups and 3D modeling; product design; statistics; designing, tooling, and prototyping in the Machine Shop, and electronic circuit fabrication and microprocessors; project management; sustainable design; marketing and how to determine price; engineering ethics and professional codes of conduct; the role of engineers in product liability and risk management; patents and the protection of intellectual property and sustainable engineering. Finally, the course concludes with lectures on business plan basics, engineering economics, and how to prepare a venture proposal.
Figure 2. Example of methodology for developing a problem statement.

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Connecticut River is polluted. It needs to be cleaned up.
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**What?**
- Do we agree on what constitutes pollution?
  - Ex. Barrel of H2O
  - Add 1 guppy
  - Add 500 guppies
  - Would you drink it?

**Where?**
- Where is the pollution? Where does it originate?
- When, why and how was it polluted?
- Who did it? Who cares?

**Why?**
- What are we supposed to clean up?
- Acceptable methods?
- Time scale for accomplishing it?
- Willing to pay how much?

**Who?**
- What constitutes the Conn River? Do its tributaries count?

**When?**
- Must be important to someone (who?)
- Won't happen by itself

**How?**
- It's possible

**The Point**
- Don't accept problem at face value
- Probe relevant issues
- Overcome biases of an implied solution

Figure 3. Outline of the iterative approach to problem solving.

**A SYSTEMATIC APPROACH TO PROBLEM SOLVING**

- Eliminate pollution
- Stop more
- Worthwhile cause
- Solution exists

- Focus problem; redefine if necessary; educate client
- Go beyond implied solution because it may not be best

- quantitate: apply math/scientific analysis
- conduct research if necessary
- ability meet specs
- model
- fabricate prototypes if necessary

**ANALYZE ALTERNATIVES**

- size
- mat'ls
- cost
- time-frame
- performance
- availability
- marketability
- reliability

**DETERMINE SPECIFICATIONS**

- envr impact
- appearance
- constructability
- legal
- political
- ethical
- safety

**GENERATE ALTERNATIVES**

- State-of-the-Art
- PATENTS
- Does a solution already exist?
By the end of the term students document and test final prototypes with target users. They then prepare for final presentation and written reports that articulate the full scope of their term-long design investigation and prototype development. Final reports must include the following elements: need finding, problem definition, analysis of target users, analysis of state-of-the-art, project specifications, testing, engineering analysis, prototyping iterations, evaluation by end users, business plan/venture proposal, and finally, future recommendations for the project.

**CONCLUSION**

During the forty-six years that ES21 has been offered, generations of Dartmouth engineers consider this course to be a career-changing experience in their engineering education. Numerous course projects have been patented and some have provided springboards to commercial enterprises.

In 1964 Dean Spatz invented a method of making contaminated water potable by developing a water filtration technology using reverse osmosis. After graduation in 1967, Dean founded Osmonics, a company that successfully exploited his initial concepts and became dominant in the field. Osmonics was subsequently acquired by General Electric.

In 2004 Hannah Murnen, Augusta Miles, Nathan Sigworth, and Deborah Sperling invented a novel gyroscopic stabilization system designed to help children learn to ride bikes. The system includes a small, spinning flywheel built into the front wheel, which imparts gyroscopic force to make it more stable for beginners, and has approximately the stability of one going at 10 mph from the moment a child starts riding. The students subsequently continued development of GyroBike, as the product is called, starting a company in 2005, receiving a patent in 2007 as well as winning Popular Mechanics Top 10 Innovation Award.

It is common for engineering programs to advocate interdisciplinary thinking while simultaneously requiring a commitment to a specific discipline. This description of an introductory engineering design course provides a window on the multidisciplinary functioning of Thayer School’s non-departmentalized program that brings together faculty with expertise in a range of engineering and science disciplines. It is a culture that encourages experts to also think as generalists who can envision solutions that cut across traditional disciplines, a critical adaptive skill for staying on the forefront of technology.