AC 2008-1571: DESIGN, THE NEXT GENERATION: A FIRST-YEAR COURSE IN PRODUCT DESIGN

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Introduction

In recent years the teaching of engineering, exemplified by ABET Criteria 2000[1], has recognized that professional engineers have to master a wide variety of skills and responsibilities—not only traditional engineering science and problem solving, but working in multidisciplinary teams and effectively communicating about their work. The challenge for educators has been to integrate this more holistic view of an engineer's training with the already demanding curricula already in place. At the University of Michigan all incoming first-year students are required to take a course, Engineering 100, "Introduction to Engineering," that integrates many of these skills—design, communication, engineering science and teamwork—in the context of a semester-long project. This course has several sections each semester, each with a different project focus. Some sections of this course go through a complete design/build/test cycle, while others, such as ours, focus more closely on the design process.

Our section, Design: The Next Generation, focuses on the product design process. Students learn about design through redesign of common consumer devices. They undertake a market analysis of the device as part of determining design objectives, undertake experimental studies on the performance of existing products, carry out reverse engineering of two models, and propose a design for the next generation of the device. As part of this experience they become immersed in the design process; design and execute experiments; use basic statistics to analyze the needs of their users and their experimental results; write technical reports and proposals; and prepare and deliver oral presentations. We also focus on the students' growth as competent team members, with an ongoing peer evaluation process that includes individual or team intervention as needed. In this paper, we provide details on the teaching of our course, and share insights that should help others planning to teach a similar course in the future.

Course overview

The outcomes that all students in the "Introduction to Engineering" course are expected to achieve are outlined in Table 1 and shown in more detail in the Appendix.

It is worth noting that most of these outcomes do not lend themselves well to a purely cognitive approach—that is one that focuses on transferring knowledge from instructor to student. In fact, it is sometimes difficult to specify exactly what the "knowledge" component of design, teamwork or communication should be. Instead, we focus on developing students' skill and confidence as practitioners in these areas by letting them work through the experience. In some areas our role is as much that of coach as it is subject-area expert.

Table 1. "Introduction to Engineering" course outcomes

After completing Engineering 100, students should be able to do the following at a first-year level.

1. Solve engineering problems using mathematics, engineering, and science concepts.
2. Analyze, interpret and make decisions about quantitative data.
3. Solve an open-ended design problem.
4. Use teamwork skills in the context of a team-based design project
5. Engage in an ethical decision-making process, given some engineering situation.
6. Identify the ethical, environmental and global and societal impacts of engineering practice.
7. Design technical/professional communications.
8. Deliver well-structured, technically sound oral and written communication.
9. Evaluate and effectively construct arguments, using technical content at the first-year level.

The technical component of the course varies by section, with some sections being very specific to a given major, such as the "Mechanics and Materials for the Design of Biomedical Devices and Orthopedic Implants." Others, such as ours, are broader in perspective. Our section, "Design: The Next Generation," focuses on the redesign of an everyday device, and appeals to a wide range of students intrigued by the in-depth focus on the design process. Alumni of the class who have gone on to Mechanical Engineering in particular have commented that this class was very useful preparation for courses in the Mechanical Engineering design sequence.

The idea for this section was an outgrowth of a workshop one of the authors attended the NSF workshop on Novel Process Science and Engineering at Rowan University College of Engineering in July 1999, where participants were introduced to the concept reverse engineering of coffeemakers as part of an overview of their Freshman Engineering Clinic [2]. The course developed into a product redesign course, following the design process introduced in Dym and Little [3] and shown in Figure 1. Taking the redesign process through to actually building products would be a formidable challenge, both in terms of time and cost, so we focus solely on the design phase. This allows us to focus more closely on the design aspects of the process, and students can work on devices that would otherwise be impractical, given the diversity of the students' academic backgrounds and our limited capabilities to provide lab space and other resources. Students focus on the users' needs, an understanding of the engineering behind current devices, and brainstorming components of the earlier parts of the design process in generating proposals for a "next generation" of their device.

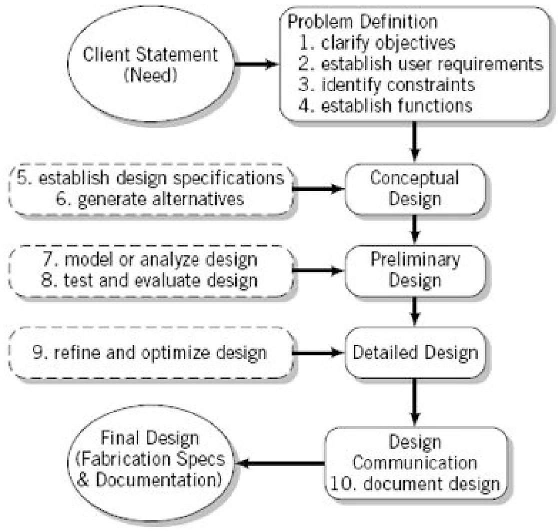

Fig. 1. Dym and Little design process steps[3]

The class is taught in 1.5 hour lectures and one 1.5 hour recitation section each week, and staffed by one instructor from the Technical Communication program and one from an Engineering department (in this case, Chemical Engineering), plus one or two recitation instructors. Standard class size is 96 students, divided into four recitation sections of 24, with six teams of 4 students in each section. One of the challenges in teaching Engineering 100 is the wide range of abilities and skills present in the student population. Whereas a student with advanced knowledge of calculus would already have credit for the introductory calculus class, every entering first year student must take Engineering 100. The result is a class with some students with no prior experience in certain areas, such as statistics, along with students who have earned advanced placement credit for advanced statistics; some students who have participated in group design activities as part of extracurricular activities, and others who have no prior design experience. This wide range of abilities introduces another challenge that must be tackled in the classroom and project portions of the course. One of our primary goals for this class, in addition to helping students master the technical content of the course, is to help them grow as responsible team members and leaders.

Project overview

The scenario for our section is that we represent New Products Incorporated (NPI), a fictitious capital investment company that focuses on subcontracting with design and manufacturing firms to bring innovative consumer devices to market, and we are seeking new partners. To that end, we are soliciting proposals for new and innovative ideas for the redesign of devices currently on the market. In addition, students are assigned to teams of four or five members, and each represents an individual design "firm" responding to NPI's request for proposals. This setup gives students some freedom to develop projects that interest them, while still imposing some of the constraints of a real design project, and creating interdependent teams that will have to learn to work together to carry out their project.

The project proceeds in several phases, as shown in Table 2, each of which builds on the previous ones. Each of these phases culminates in a report or presentation detailing the teams' findings or proposals. At each of these major milestones, students undertake an assessment of their performance so far, their teammates' performance, and that of the team as a whole. These assessments are reviewed by the course staff and shared with the students themselves. At least three times a semester, each team meets with a member of the course staff to review their progress and get suggestions for their next steps.

Table 2. Project phases

Initial project proposal	Teams generate a number of candidate products for redesign, and converge on one that they will focus on for the remainder of the project.
Project plan	Teams produce a tentative breakdown of project tasks and a Gantt chart for completing the project.
Objectives Analysis	Teams define the objectives (requirements) the devices should meet, based on their own analysis and research, and a survey of users.
Benchmarking	Teams specify quantitative and qualitative performance targets for their redesigned device, based on their experiments on two existing models.
Functional analysis	Teams determine the device's functions and the engineering principles that underlie them, based on reverse engineering the two existing models. This involves accounting for inputs and outputs of energy and materials as they flow through the system.
Design proposal	Teams propose designs for the "next generation" of their devices, which meet the objectives defined above and offer functional improvements over the current models. Teams are expected to incorporate design for manufacturability, environmental impact, and other "Design for X" issues.

The lead instructors play the role of Managing Directors of NPI, and recitation instructors that of Project Supervisor, who work more closely with the teams. In the following sections we describe each phase of the project and denote the course outcomes that are addressed within each phase.

Initial project proposal

In the planning phase of the project teams go through a process to decide on two devices that could be improved to propose to us. The class as a whole develops a set of criteria for a good project based on the overall project memo. The criteria developed for the Winter semester of 2008 are shown in Table 3. Then students propose two device ideas to their team, and after a discussion regarding how well each of the proposed devices best fits the criteria, each team proposes two devices to work on for the duration of the project. These two devices are presented to course staff in an oral presentation to management within their recitation sections. The course staff then approves one or both of their projects. Students acquire two models of their project device for study, with costs reimbursed by the course.

Table 3. Criteria for acceptable project devices (2008)

Acceptable devices for this project must:
- Cost under $50 in average ($100 total)
- Be safe to operate and to analyze
- Have potential for substantial functional improvement
- Be able to be disassembled and analyzed
- Have objectively measurable functions (i.e., experiments can be performed)
- Have functions based on understandable engineering principles
- Have enough users available to do a survey of
- Be robust (not too fragile)
- Have multiple models or types

The method by which they determine the devices for their projects has evolved over the years from an informal one toward a more structured process, in which teams generate and then evaluate multiple design ideas against the criteria above. This ensures all team members get a chance to have their ideas heard, and models the overall design process in miniature. A sampling of devices students have worked on over the years, shown in Table 4, gives a sense of the breadth of possibilities A wise choice of devices is critical to a successful projects. While it is tempting sometimes to let students explore offbeat ideas, it is important to consider all upcoming steps in the design project to make sure the team will be able to complete it successfully. For example, every year some students will come up with creative ideas for a new device all together. While it would be a great project for them to explore the design of such a device, it does not lend itself to experiments using existing devices or the reverse engineering of existing devices, and as such would not make for a good project for this course.

Table 4. Selected devices from seven years of course offerings

Air freshener	Floor mop	Reading light
Alarm clock	Food mixer	Retractable pet leash
Aquarium filter	Food processor	Salad spinner
Backpack	Hairdryer	Self-powered flashlight
Bagel cutter	Handheld vacuum	Smoothie maker
Blender	Headphones	Sno-cone machine
Coffee bean grinder	Ice cream maker	Stapler
Computer mouse	Juicer	Toaster
Desk lamp	Lawn sprinklers	Umbrella
Electric can opener	Nerf gun	Vacuum cleaner
Electric pencil sharpener	Orange juicer	Video game controller
Electric toothbrush	Popcorn popper	Waffle iron
Fishing reel	Razor	Water gun
Fishtank water pump	RC car	Water purifier

Project plan

Teams have to learn how to organize their efforts and manage themselves. First year students are often naïve about the amount of time and organization goes into a successful project, and they wind up reacting to deadlines rather than working at a steady, sustainable pace throughout a project. Asking them to look at the whole project as a series of tasks to be completed, and mapping that onto a calendar that is also full of other classes, social activities, and the obligations of other team members brings home the necessity of planning. This is one way in which, rather than focusing merely on the technical aspect of the project, we aim to provide our students with transferable skills they can use in future courses and generally in their careers.

This begins with a project plan, in which they begin with the broad tasks outlined in Table 2 above, and break them down into smaller, more manageable tasks, with rough estimates of how long they should take and when they need to be completed. This is summarized in the form of a Gantt chart and described in the body of the report they submit. A meeting with course staff follows to provide teams with feedback on their plans.

Typical errors seen in team Gantt charts include failing to divide the work between members, or, at the opposite extreme, assigning tasks so atomistically that a coherent overall vision is lost. These typically are symptomatic of deeper problems—wanting to work together on all aspects of the project, for example, often comes from a lack of trust and confidence in one another, whereas totally compartmentalizing the project between team members may reflect a general unwillingness to lead on the part of individual team members. In these cases, the project plan can serve as a diagnostic for team problems and a reason to intervene.

Objectives analysis

In this portion of the project students learn to listen to the "voice of the customer" and to focus on product objectives and possible redesign opportunities, rather than jumping ahead to solutions they already have in mind and limiting their design space. Objectives, captured in a hierarchical "objective tree," such as the one shown in Figure 2, describe required properties of a product, such as *safe*, *clean*, or *user-friendly*. In this portion of the project teams must define a set of objectives for their devices. They refine high-level goals (such as *safe*) into more detailed, measurable objectives (such as *shockproof*) that can be used to guide the rest of the design process and assess the success of the final design. Since there may be tradeoffs between objectives (cost versus quality, for instance), some idea of their relative importance needs to be established.

i. Portable
    1. Small
    2. Lightweight
    3. Cordless or battery powered
ii. User Friendly
    1. Satisfying results
        a. Sharp point
        b. Sturdy point
        c. Even point
    2. Safe to operate
    3. Durable
    4. Quiet
    5. Easy to clean
    6. Within average market price range
    7. Fast
iii. Versatile
    1. Variety of tips
    2. Compatible

Fig. 2. A sample objective tree for a pencil sharpener

Preliminary objective trees may be generated by brainstorming and informal market analysis, but as drivers for the rest of the project they need to be justified by reasoning and evidence. A primary tool is the gathering of customer data through surveys of typical users. In the past surveys presented some logistical challenges, but they have become less onerous with the advent of web-based survey tools such as Survey Monkey. Besides providing design goals for their project, the surveys are a chance to learn about basic data gathering and statistical concepts (sampling, measurement, simple descriptive statistics) in the design and analysis of their surveys.

After analyzing their survey data, teams submit the first of three reports. This first report includes an analysis of the objectives, including an objective tree, as well as summary of their research, including analysis of their survey results and other background research. Besides making each writing task less onerous, having multiple reports allows the teaching staff to offer several iterations of the report writing process, and students can then incorporate the feedback from each one into the next.

Benchmarking

In this portion of the project teams perform experiments to determine how well the two current models achieve some of the objectives and perform some of the functions. Teams must decide which aspects of their devices need to be evaluated, design and carry out experiments, analyze their results, and draw conclusions about the relative performance of their two models This sets minimum standards (benchmarks) for the redesign of their device, and suggests possible directions for improvement. As before, a report documents the data obtained and the conclusions they come to.

For many students this is the most enjoyable part of the project. They come together as a team as they develop creative ways to analyze the performance of devices, and they start to build confidence that they do have valid ideas for improvement. This past year, for the first time, teams had access to the equipment listed in Table 5 for use either in the college's student team center, as shown in Figure 3, or to check out for use in the dormitories. This has made it easier for students to develop experiments, although some students from previous sessions have commented that they appreciated the challenge of designing experiments without access to such equipment, resulting in creative ways to measure performance.

Table 5 – Equipment available for benchmarking experiments

Windspeed and temperature meters
Light meters
Decibel meters
Pyrometers with range 32-500 F
Dynamometers, 5 lb_f (0.5 lb_f), 30 lb_f (0.25 lb_f), and 60 lb_f (0.5 lb_f)
Balances, 410 g (0.1 g) and 4100 g (1 g)
Sieves with mesh sizes 0.5, 1, 2, and 2.36 mm
Graduated cylinders at 10, 25, 100, and 250 ml

Fig. 3. Students at work performing experiments on existing devices

Functional analysis

To deepen their understanding of how their devices work and how they might be improved, teams now perform a functional analysis of the existing devices to better understand the operation of the device. This includes several steps, including:

1. Developing a process description, outlining in detail the process users go typically through when they use the device;
2. Taking their devices apart and analyzing their workings in order to understand how they function (reverse engineering); and
3. Developing a functional description of their device, which accounts for all energy and materials that enter the system, how they are transformed as they flow through the system, and how they are output as intended and waste products.

This part of the course is very satisfying to many students, who originally got into engineering because they like hands-on problem solving and exploration. Often students get a surprise or a sense of the engineering ingenuity that goes into products that they weren't aware of. As an example, we introduce them to this process by devoting two days in class to disassembly and functional analysis of a standard countertop coffeemaker, which uses familiar and unfamiliar scientific concepts such as resistive heating, heat transfer, vapor pressure, and leaching [2]. Each team gets a coffeemaker and performs the three steps above, as seen in Figure 4. Students often assume there is a pump which raises hot water and have to rethink their assumptions when they discover that there isn't one, or discover that the element that heats the water and the element that keeps the coffee warm, although functionally distinct, are in fact the same thing.

Fig. 4. Students at work on coffeemakers during class

It is this focus on discovery, analysis and scientific reasoning we are trying to cultivate when they apply this process to their own projects. In their report on this phase they include schematics or photographs that clearly display the key components of each device, a refined function structure for each device showing how inputs are translated into outputs, and an analysis of two primary functions the devices perform, including detailed descriptions of the overriding engineering principles.

Design proposal

Once teams have learned all they can from existing devices, they brainstorm ideas for design improvements. Teams generate morphological (function-means) diagrams outlining various means to perform the device's key functions, such as shown in Figure 5, and from these develop four candidate designs representing four possible approaches to the design problem.

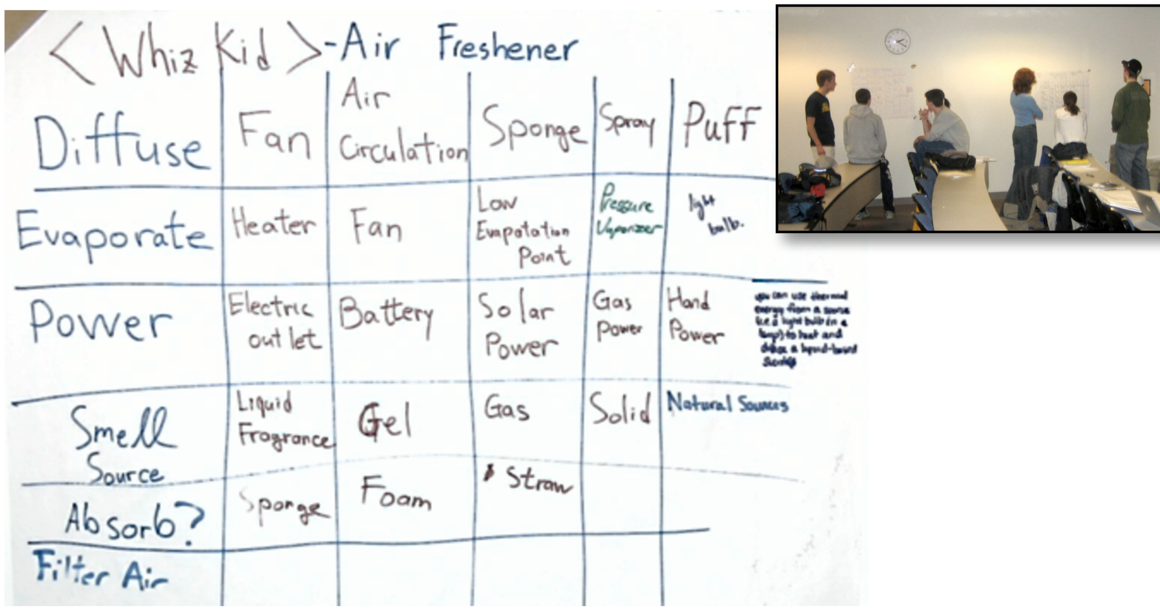

Fig. 5. Function-means diagram from an in-class work session in which teams review each others' ideas (inset). Note that other teams have added ideas and suggestions to the originals.

They evaluate these based on a set of weighted criteria representing the design constraints and objectives. This is an embryonic version of the more complex decision making processes, such as Quality Function Deployment (QFD) that they will encounter in more advanced engineering courses.

The teams' proposed designs represent the ultimate result of this process, and pull together all the work they have done over the course of the semester. They present a preliminary version of their design orally, with schematics and function structures. Their design choices have to be justified, and various questions addressed: how their design meets the users' needs, and how it incorporates (or innovates on) the best of the devices currently on the market Finally, they develop a final written design proposal, taking into account feedback from the course staff, and considering issues of manufacturing, reliability, maintainability, affordability, accessibility, and environmental impact issues.

We allot two weeks between the oral presentation and the final written proposal to allow teams to implement suggestions received in the oral presentation. The oral presentations are scheduled in sessions of 4–6 presentations, with the audience consisting of the management team and the other student teams, and occasional outside visitors, interested faculty, and others. Students are encouraged to provide other teams with ideas and suggestions to improve on their design. Since the class is graded on a straight scale there is no cost to them, and this has resulted in many insightful suggestions.

The role of the communication and teamwork components

The design process is the logical and scientific core of the course. Woven through it are strands involving the teaching of professional communication and effective teamwork. A key assumption of the first-year course is that higher-level skills can be taught, even at the first-year level, by grounding them in real practice. Certain skills can really only be taught through practice and this is true of the broad continuum of skills ranging from written expression to organizational communication to interpersonal communication to small group skills such as working in teams. Incoming students often initially misunderstand the nature of these tasks, having been presented with one-time "group projects" in place of genuine teamwork, and in decontextualized term papers and five-paragraph essays in place of engineering reports.

This is especially true in the realm of communication. Fundamental aspects of the writing situation are opaque to students: the goals of communication in the workplace; the role of expertise, authority and experience; membership in the "discourse community" of their peers, understanding of how readers read. Our goal in this course is to let them experience these issues for themselves. Thus, in the major project reports, they have to learn basic rhetorical skills, such as determining the purpose of the report, and then write to that. By working through the project for themselves, they begin to develop the sense of authority and competence that a professional needs to have in order to communicate successfully.

Above all, they must learn to approach writing, like design, as a process. Students tend to be product- instead of process-oriented (and teachers sometimes encourage this by stressing surface features of form and organization in our evaluations). However, workplace writing, for any but the simplest documents, involves multiple steps of analysis, invention, writing, feedback and revising. This course asks students to adopt, at least temporarily, the workplace paradigm. As reports accumulate, and get evaluated, reused and revised, students begin to approximate a real professional writing situation. For example, they rehearse presentations with course staff and use the feedback to refine their material, then repurpose their oral material to work in a written format. And since these are all team efforts, students have to begin developing effective models of collaboration.

Since this course is for most students their very first introduction to a professional model of communication (as opposed to creative or expository writing), a certain amount of "scaffolding" is needed. Early assignments are assessed mainly on the basis of how well they follow genre conventions, and then as the semester proceeds, additional elements are foregrounded and assessment becomes more comprehensive. For instance, the first presentation is mainly aimed at presenting information in an orderly, structured way; after that, the demands become more complex, as more issues are introduced (problem definition, audience analysis, argumentation, visual communication, oral communication, and finally prose style). At every point, new ideas are contextualized in terms of the underlying issues of communicating in organizations and with specific purposes. At the end, our goal is for students to work—within the limitations of their first-year curriculum—in a professional framework (though perhaps not yet at a fully professional level).

Similarly, students often have oversimplified notions of what a team project is like. They may imagine that all team members will become friends and do everything together; or they may imagine that if they split the work up and each team member does a good job with his or her portion, then the parts will join up into a high-quality whole. In reality, teamwork demands much more flexibility and adaptability, in which focused collaboration is as important as high-quality individual work. In order for students to see this, they have to be placed in a situation where the simpler strategies *cannot* succeed: a long-term situation in which everyone has to develop expertise, contribute, collaborate and be accountable to each other.

To help our students develop as team members we make extensive use of peer evaluations throughout the semester, in which students evaluate themselves, each of their team members, and the team as a whole along three dimensions: Technical and technical communications results, meeting goals and deadlines, and teamwork. They assign numerical values using the criteria in Table 6, based on a teamwork model developed by Barkel [4], and list strengths and suggestions for improvements.

Table 6 – Criteria for peer evaluations

RESULTS (TECHNICAL AND TECH COMM) (0-4, increments of 0.5 OK)

4 (Extremely competent, knew everything, did solid work) 3 (Very competent, figured out what to do, confident in results), 2 (Partners had to check work, but everything was pretty much OK), 1 (Partners had to redo some of the work, some was OK but there were a number of errors), 0 (Partners had to redo all the work)

MEETING GOALS/DEADLINES & COMMUNICATION: (0-3, increments of 0.5 OK)

3 (Met all deadlines with complete work without reminders, initiated communication), 2(Met deadlines, answered emails), 1 (Submitted work past deadline, eventually answered emails, didn't initiate communication), 0 (Didn't submit his/her/my part of the work, impossible to reach)

TEAMWORK: (0-3, increments of 0.5 OK)

3 (Contributed to positive spirit of the team, helped others with their work as needed, instrumental in getting final version completed), 2 (Strong team member, got own work done and helped others when requested), 1(Completed own work only), 0 (Not a team player, seldom showed up to scheduled meetings, unprepared, or brought a negative attitude to team)

Students are instructed that they will encounter this peer review process in their careers, so that it is important that they learn how to provide feedback professionally and diplomatically, and also to receive and learn from feedback. Each student receives copies of all evaluations about them, with the name of the evaluator kept private. These evaluations help strong team members feel appreciated for their efforts, and give weaker members an opportunity to improve their performance. Teaching staff review all peer evaluations and can intervene as needed either individually or with a poorly functioning team. In addition, teams are asked to document many aspects of their team experience, with meeting agendas, decision logs, to-do lists, research and experimental results and more. These records are reviewed periodically by course staff.

The result of this labor-intensive process is that the instructors are very familiar with the teams and the individual students and highly aware of their day-to-day progress. In a large university with very large classes in the first year, this provides an unusual opportunity for students and instructors to get to know one another. We feel it has paid off both in personal growth on the part of the students, but also improved performance. Time spent heading off trouble early on and helping students find ways to work more effectively pays off in the end; the conflict and unpredictability associated with student teams under stress seems more manageable.

Conclusions

In this paper we have outlined the elements of what has been a successful introduction to engineering course that focuses on the design process and its technical, technical communications, and teamwork elements. The project components allow students to experience this content with repeated feedback, and a gradual ramping of expectations throughout the term. A very hands-on approach on the part of the instructors results in more positive team experiences and growth of students as team members.

Acknowledgements

The authors would like to thank the organizers of the Rowan University Freshman Design Clinic for planting the seed that resulted in this course. They are also deeply grateful to the hundreds of students of our course over the years, whose hard work and dedication has made it a pleasure to teach this class and has inspired us to continually improve it to provide a meaningful and useful experience to future students.

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Appendix – "Introduction to Engineering" course outcomes

1. Solve engineering problems using project-specific mathematics, engineering, and science concepts.
2. Analyze, interpret and make decisions about quantitative data using basic concepts of descriptive statistics (mean, median, standard deviation, normal distributions, and mode) and measurement, including issues in:
   a. precision and accuracy;
   b. sample and population;
   c. error and uncertainty.
3. Solve an open-ended design problem by:
   a. transforming an open-ended design problem into an answerable one;
   b. breaking down a complex design problem into sub-problems;
   c. determining assumptions involved in solving the design problem;
   d. determining resources that can be used to solve the design problem and how to obtain these resources;
   e. determining multiple possible design solutions to the design problem;
   f. selecting a design solution using a well-defined method appropriate to the problem domain.
4. Use the following skills in the context of a team-based design project:
   a. develop clearly defined, explicitly agreed-on project goals;
   b. develop and implement a project plan;
   c. conduct effective team meetings;
   d. document team activities;
   e. evaluate how well the team and individual team members are functioning (using team norms and a knowledge of good team practices).
5. Engage in an ethical decision-making process, given some engineering situation:
   a. analyze the situation (using a appropriate method or framework);
   b. decide on a course of action (using relevant codes of ethics);
   c. support this decision.
6. identify the ethical, environmental and other global and societal impacts of engineering practice.
7. Designing technical/professional communications by employing the following skills:
   a. analyzing a communication situation so as to determine the audiences and their information needs and a purpose and rhetorical approach for the document or communication;
   b. breaking a communication task into components and employ appropriate strategies at each stage of the communication process (both individually and collaboratively);
   c. writing readable prose, as characterized by well-organized paragraphs, well-constructed sentences, precise and effective use of both non-technical and technical vocabulary, and adequate and appropriate use of transitional devices;
   d. organizing information for oral presentation;
   e. creating clear, accurate graphics that are well integrated into oral and written communications, including both quantitative graphics (charts/graphs) and representational graphics (diagrams/illustrations).
8. Deliver well-structured, technically sound communication of the following types:
   a. well-formatted informal and formal written reports;
   b. oral reports, given without notes and with supporting visuals.
9. Evaluate and effectively construct arguments, using technical content at the first-year level.