Developing Aspiring Engineers into Budding Entrepreneurs: An Invention and Innovation Course*

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ABSTRACT

Our invention and innovation course for engineering students cultivates an understanding of the entrepreneurship and invention world through a hands-on introduction to product design and development. A pervasive emphasis on team dynamics as well as on the process of design, invention and innovation fosters an environment that produces successful teams and inventions. This paper describes objectives and components of the elective course, development of high-performance invention teams, course evaluation, assessment tools and results, and lessons learned.

Students working in teams design and build an invention of their choice, and explore entrepreneurial topics such as profitability, marketing, sources for capital, and patenting. Creating business feasibility studies leads each team to estimate the manufacturing cost of their product and forecast potential sales revenues and profits. A two-week, low-risk introductory creativity and design project provides an early opportunity for creative expression, as well as insight into individuals’ contribution and effectiveness in a team environment.

Our course was inspired and initially supported by the National Collegiate Inventors and Innovators Alliance (NCIIA). Some student teams have subsequently received NCIIA product development funding.

I. INTRODUCTION

At CU-Boulder, first-year engineering students experience a hands-on introduction to engineering through an interdisciplinary projects course. Inspired by both the success of this early design experience and the impressive capability of younger engineering students to create challenging and robust products, we developed an innovation and invention course. Offered for the last three years and targeted to more mature students, many of whom either transferred into engineering later in their academic careers or delayed taking the first-year course, the integration of an entrepreneurship component into the traditional design-build cycle has a significant appeal to these students.

This invention and innovation course focuses on entrepreneurship—product development and taking a new product to the marketplace. A team-based product design and development project integrates an introduction to engineering design with product innovation. As students explore the invention process through hands-on doing, they learn other valuable engineering skills as well. These abilities include oral and written communication skills, feasibility study development, and use of computer-aided design, all fundamental tools for fully exploring product innovation and invention. A pervasive and sometimes relentless focus on team effectiveness often makes students initially uncomfortable, but usually results in high performance and happy, productive teams. The student work exploits the state-of-the-art fabrication capabilities of the Integrated Teaching and Learning (ITL) Laboratory’s Manufacturing and Electronics Centers.

While a major focus of this course is on product creation, an underlying and equally important course objective is to teach students the process of invention and product innovation. Students learn that having a great idea or “making a cool gizmo” is only the beginning of their product innovation journey that will include product prototyping, understanding whether potential customers need or want their product, exploring the competitive advantages of their product, learning to navigate the intellectual property issues associated with patenting, and gaining an understanding of the impact of manufacturing processes on product profitability. This lesson is an eye-opener for most engineering students, who assume that a market exists for their product ideas and that somehow taking a product to the marketplace just happens. This course is considered successful if students experience the process of product invention and innovation, come to realize that understanding the customer and market are critical for their inventions to find a niche, and

understand that their inventions must reach the market in order to have an impact on the world.

II. COURSE STRUCTURE AND ELEMENTS

Enrollment is limited to 30 sophomore-level and above, or transfer students. Course enrollment is open to non-engineering students as well. The three-credit-hour, 15-week course meets for one interactive lecture hour and two, two-hour studio weekly. Teams work on their inventions during most studio periods; however, formal design reviews and other team exercises occur during studio periods as well. One such team experience is meeting weekly with us, the instructors, to review project progress and set specific goals for the following week.

A two-week, creative foam core design project initiates the semester, introducing students to working under deadline pressures with their new team. The exercise breaks down communication barriers, emphasizes the creative process, and alerts both students and instructors to the unique team dynamics and communication challenges that face each team. Students engage in the exercise and produce creative results, but some students find it uncomfortable to be held highly accountable by their teammates through engagement at such a deep interpersonal level. Despite discomfort, we use the exercise because it improves student’s skills in team brainstorming techniques, team dynamics, and unleashing the creative process.

Interactive lectures throughout the semester provide students with a real-world perspective on various aspects of the invention and innovation process. Entrepreneurship discussions focus on the business perspective of innovation: analyzing the customer desire or need for a product, quantifying market size, estimating profitability, and researching the potential for product patenting. Other discussions explore topics common to the invention and design-build-test cycle, including stages of the design process, creativity simulation methods, decision analysis methods and aesthetics in design.

A brainstorming session during the first week of the course generates product ideas and introduces students to brainstorming as an important creativity tool. From this session a list of products emerges that engages student interest and is relevant to their lives. Student voting narrows the list to a short roster of potential products. We eliminate projects that are too complex in scope, and take individual product preferences into consideration as teams are formed.

Early-in-class workshops focus on general topics important to engineers, such as communication skills and styles, creativity and team dynamics. Workshops later in the semester help students develop hands-on skills needed for product development, such as computer-aided design (CAD), basic electrical circuits, safety and use of machining tools. Each student contributes a maximum of $50 toward materials for product development. In addition, a course textbook, *Introductory Engineering Design: A Projects-Based Approach*, is available (but not required) for $20, self-published by a team of CU engineering instructors.

A formal team poster presentation is required at a Saturday Design Expo in which students showcase their projects to the public. External judges evaluate product quality and students’ understanding of the fundamental technical and business concepts surrounding manufacturing and marketing of their product.

III. THE HUMAN SIDE: DEVELOPING HIGH-PERFORMANCE INVENTION TEAMS

Creating a climate in which invention and innovation thrive requires early and persistent attention to team dynamics. Productive, high-performance teams rarely develop in one semester—but groups of students can be nurtured to evolve more rapidly into high-performing teams if immediate and intense attention is given to team dynamics.

Our experience is that successful team dynamics and product invention go hand-in-hand. An emphasis on the communication process and teamwork is pervasive throughout the course. Instructors and students learn everyone’s name in the first class session through experiential icebreaker exercises targeted at creating a risk-taking, playful and respectful classroom environment. Name use is reinforced at each class meeting until names become common and comfortably used by all. A Week 1 social and communication styles workshop also serves to create a common language wherein differences in each student’s communication style are recognized and understood. The workshop seeks to increase awareness and value for the different ways people interact and draws attention to the prejudices everyone brings to the group communication processes. Team dynamics and team-based logic exercises provide fun, moderately physical activities in which teammates work together to solve a variety of challenging problems. These exercises further break down barriers and create a class environment where risk taking is encouraged, celebrated and rewarded. During these early workshops, students are taught how to publicly give and receive positive and constructive feedback. Students give verbal feedback by highlighting two items that they think about a project (‘I like...’) accompanied by one suggestion for improvement (‘I wish...’). Gathering insights on each student’s potential contribution to team success through group problem solving exercises and an interactive social style workshop, we assign teams of four to six students each at the end of Week 1. Skill and knowledge sets, social styles, product preferences and gender are balanced within teams. When possible, students are paired within a team to minimize their potential for being dominated in predominantly male teams. As our student population is approximately 20 percent female, this results in some male-only teams, while other teams may have one or two women team members.

During Weeks 2 and 3, the intense creativity four-core exercise causes team dynamics challenges to surface (see Figure 1). Throughout the exercise, respectful and constructive critique techniques are employed, and a confidential peer and self-evaluation is performed at the end of the exercise. The peer evaluation results factor into each student’s grade, with specific feedback provided in a one-on-one setting with the instructors. This early opportunity to struggle and succeed/fail at team effectiveness provides floundering students with the chance to learn and start fresh on the main component of the course—the invention and prototyping of a new product.

The first three weeks of a team-based invention course are critical. By the end of the three-week period, students should be in a climate in which everyone knows one another; ideas are openly shared; all opinions are given a respectful hearing; and constructive criticism is graciously accepted, if not always welcomed. Modeling supportive and respectful behavior, we expect every student work group to develop into a productive and respectful team. Setting this
expectation at the beginning of the course, and creating a classroom environment in which students are empowered and creativity flourishes, are keys to student team success.

Throughout the semester, we continuously coach the teams and reinforce the concept that the overall objective is team success. At weekly team meetings, team effectiveness is a routine topic of discussion. Additionally, teams are expected to include candid assessments of their effectiveness at each of three class presentations. This continual emphasis on the process of teamwork is critical to help individual members accept that the process of invention, including learning to work in a high-performance team, is as important to success in the course as the quality of their product.

A team-written “team effectiveness” paper at mid-semester results in student teams openly addressing unresolved team difficulties. Students typically find this soul-searching task difficult and uncomfortable, yet later comment on its value. For some teams, this exercise becomes a turning point; they finally understand that the well-functioning teams are having fun and experiencing a high degree of accomplishment. At this stage, even the most ardent individual performer begins to contribute as a team member.

IV. PRODUCT INVENTION

A major course objective is the invention of a useful product. Completing this 12-week assignment is each student's opportunity to experience the design-build-test cycle. Teams use the four hours of weekly studio time to evolve through the phases of product design, including defining design requirements, generating alternative design concepts, exploring decision methods to select a design, using appropriate engineering analysis to guide design decisions, product fabrication, testing and iteration (see Figure 2). Patents of similar products are evaluated to inform and promote robust designs. Each student keeps a design journal. Preliminary and critical design reviews hone oral presentation skills, keep the entire class informed of progress, and explain the underlying reasons behind design and manufacturing decisions.

Course meetings are held in a design studio in the ITL Laboratory. The design studio provides group work areas, workbenches with small hand and power tools, “smart” projection capability, storage space and one computer per team (including SolidWorks® CAD modeling software). Available resources include a CAD/CAM teaching assistant and an in-class undergraduate teaching assistant. In addition, students have access to the state-of-the-art fabrication capability of the ITL Laboratory, allowing them to realize their dreams. The Manufacturing Center includes CNC (computer numerically controlled) milling machines, a CNC lathe, two CNC laser cutters, conventional machine tools and a rapid prototyping system. The Electronics Center features fabrication, measurement and testing equipment. Both facilities are professionally staffed.

V. PRODUCT INNOVATION

Another major course objective is each team's determination of their invention's market potential. Characteristics of entrepreneurs, sources of financing, profitability, pricing and intellectual property issues, and marketing considerations are explored. Carefully selected and well-prepared guest inventors spark student interest by sharing their personal successes and setbacks. A guest "angel" investor discusses the criteria that convince investors to fund new ventures. An engineering consultant helps students estimate the manufacturing costs of their designs, which they in turn factor into a profitability equation.

Each team prepares a written feasibility study. Many teams conduct market surveys to gauge potential sales volumes, as well as what potential consumers are willing to pay for the new products. Patent searches reveal the extent of competition and avoid patent infringement.
VI. COURSE GRADING

Seventy percent of each student's course grade is based on team performance and deliverables. Factors include the creativity project, design review presentations, overall product quality and completeness, and thoroughness of the business analysis and feasibility study. The remaining 30 percent of each student's grade is determined by individual contributions, including two peer evaluations. In addition, we evaluate each individual's contribution to team success.

VII. EVALUATION AND ASSESSMENT

Great emphasis is placed on continual course improvement. Prior to the initial course offering, we developed a detailed assessment plan and matrix that identified nine specific course goals. For each goal, we determined learning objectives (what each student should be able to do and know at course completion) and mapped each to specific ABET criteria. Next, we established the performance level required to meet each learning objective. The evaluation methods we employed were designed to collect data and assess student performance against each performance criteria. As a result, we developed a variety of assessment tools that continue to evolve with the course. Assessment tools include a facilitated student group interview session, weekly instructor meetings, written peer evaluations, pre- and post-course skill evaluation surveys, and the university-required faculty course questionnaire (FCQ). After the third course offering, we were satisfied that we had achieved balance between the invention component (developing a new product) and the innovation component of the course (taking that product to the marketplace).

A. FCQs

Summarizing results of the FCQs administered at semester-end over three course offerings finds that students rate the course as a good learning experience (3.5/4.0 = "A-"), but that the workload is too heavy for the credit given (7.2/10 where 5 is OK), yielding an overall course rating of "B+." The FCQ assessment does not provide adequate detail for incrementally improving the course, and is thus augmented with an end-of-semester student group interview feedback session and pre- and post-kill evaluation surveys.

B. Student Group Interview Feedback Sessions

At the conclusion of each semester, an outside facilitator solicits feedback for course improvement through an in-class student group interview evaluation process. All aspects of the course (professors, projects, entrepreneurship and other discussions, specialty workshops, guest speakers, facilities and equipment) are discussed. With the instructors and TAs absent, newly formed groups averaging five students each spend 10 minutes discussing and creating a list of course strengths, recording only those on which the group reaches consensus. Each issue must be worded so that other students can later agree or disagree with the statement. During the next 10 minutes, the groups prepare a list of suggestions for course improvements, wording the suggestions specifically such that instructors could act upon them for the next course offering (e.g., "change the electronics workshop to include breadboard design" vs. "the electronics workshop is not effective"). After each small group has completed both lists, all listed items are compiled into one master list on the classroom board for all to see. Each student individually and anonymously votes on a computer-generated "bubble" form the degree to which s/he agrees or disagrees with each statement on a scale of one to five. A recorder also takes notes during this session, anonymously capturing exact student quotations. Reviewing the highlights of student feedback from this process at the conclusion of the three course offerings, most students agree that the course's main strengths are:

- The class is fun
- Establishing an encouraging learning environment
- Creating meaningful products with real-world potential
- The hands-on design and build learning experience
- Taking a broad approach to invention, including the entrepreneurial and patenting aspects of product development
- Freedom to choose the product to invent
- Enthusiasm of instructors
- Receiving candid feedback
- Developing well-matched teams
- Presentation experience
- Showcasing their product at the public Design Expo
- Quality of the resources available for product design and fabrication, including helpful manufacturing and electronics technicians

Suggestions for course improvement were most often related to specific assignments or facilities issues, and usually led to course improvements in successive years, as most have been implemented. Suggestions included (followed by resulting response):

- Give more course credit, or drastically reduce the workload (see discussion below).
- Make sure co-instructors are consistent regarding expectations and constraints (this team-teacher challenge was resolved by year three).
- Require either a business feasibility study presentation or a written feasibility study, not both (the feasibility presentation was eliminated in year three).
- Scale back portfolio requirements (portfolios were entirely eliminated in year three).
- Invite more outside inventors as guest speakers (implemented in years two and three with a high [89 percent] student satisfaction rating).
- Provide more effective workshops in 3-D modeling (plans are in place for this).
- Expand evening availability of the Manufacturing Center (implemented in year three).

Students clearly enjoy the course, but struggled with the heavy workload in the first two offerings. Early alterations to the course—the addition of more creativity and team dynamics exercises, and significantly greater emphasis on the entrepreneurship components—in fact, increased the workload to an unacceptable level. Assessment data substantiated this: after the first offering of the course, 93 percent of the class agreed that the workload was inordinately heavy for the credit hours received; 100 percent found the same after the second offering. In the third year, the workload became more manageable by eliminating time-consuming portfolios, reducing team presentations from four to three, and requiring fewer reflective writing assignments. This improvement was confirmed by recent data showing that 50 percent of the class found the workload too heavy—a great improvement. Minor course revisions will be made for the fourth offering to make more time available for students to focus on their product invention and innovation, and conduct more thorough profitability analysis.
C. Peer Evaluation

Two peer evaluations, each comprising five percent of the course grade, encourage students to take their contribution to team success seriously. The first evaluation is conducted at the end of the foam core creativity exercise, and the second after completion of the product invention. Each student divides a hypothetical $1,000 bonus among all team members (including him/herself) accompanied by a rationale for the distribution. Student results are thoughtful, and usually confirm the instructor observations. Averaged results provide a clear picture of each team's high and low achiever. Typically, low achievers rate their own contributions higher than their teammates', although they usually do not rank themselves as low as do their peers. We meet privately and briefly with each student after the first peer evaluation, helping the student to better understand their peer's perceptions of their contribution and develop strategies for improving their contribution (if warranted). This meeting can be a significant turning point in the course if students come to understand that being clever and superficial is not enough to pull their weight in the team.

An optional end-of-course individual feedback session is also offered to students; about 2/3 of them participate. We also invite feedback at this "exit" interview.

D. Innovation Skills Assessment Surveys

Since a major course intent is to improve students' innovation skills, a self-assessment skill and knowledge survey was administered at the beginning and end of the course in years two and three. Of the 31 topic areas surveyed, 14 resulted in statistically significant increases (see Figure 3). The largest improvements in student's perceptions of their skill and knowledge were in patent knowledge and search capability; recognizing the need for iteration in design; understanding of entrepreneurial aspects such as market analysis, profitability evaluation and obtaining investment capital; and use of appropriate presentation graphics. Students also reported significant knowledge and skill improvement in their awareness of environmental and universal design concepts, appreciating the contribution of data analysis and incremental testing to product design, understanding functional requirements, developing a product within specifications and a constrained budget, early use of physical models, and the value of keeping an invention journal. Lastly, significant student growth was reported in their ability to self-assess through writing of thoughtful and introspective reflections that include objective self-criticism.

Of note are skill areas in which students initially rated themselves as performing well or very well (four or higher on a one to five scale) and reported no significant improvement at the end of the course: demonstrating resourcefulness, practice of effective teamwork skills, ability to resolve conflict in a team environment, taking responsibility to accept and complete tasks and ability to conduct an Internet search. Since we know, anecdotally, that many students made great learning strides in these areas during the semester, it is hypothesized that students became much more aware of what successful performance really was during the course of the semester. Not knowing how they rated themselves at the beginning of the semester, they actually rated themselves marginally lower at semester end. To investigate this, in future post-course skill evaluations, students will also rate their recollection of their beginning-of-semester knowledge and skill levels as well as their skills and knowledge at the end of the semester. With this information, a comparison can be made between students' initial pre-course rating, and their end-of-semester pre-course rating, to see if they viewed their pre-course skill proficiency level different at the course's conclusion.

![Figure 3. Statistically significant pre- and post-course skill evaluation survey results.](image-url)
VIII. LESSONS LEARNED SUMMARY

The creation of our Invention and Innovation course parallels the product design process: the course improves with critical feedback and iteration. Some course lessons learned include:

- Create an expectation for highly functional teams.
- Maintain a relentless focus on the human side by reinforcing name use, and cultivating a shared awareness and value for varied communication and social styles.
- Create a class environment that rewards creativity and risk, and commands respect.
- Relentlessly focus on process as much as product.
- Adjust the timing of course assignments so that students can focus solely on product completion during the intense period just before the Design Expo at semester end.
- Eliminate student portfolios; they did not yield learning results commensurate with their time investment.
- Incorporate entrepreneurship topics such as profitability, marketing and financing into the course via instructor presentations, instead of Business School guest lecturers, to provide course consistency and relevance to the student inventions.
- Prepare guest speakers to weave their presentation content into the course topics and have them bring hands-on props (e.g., prototypes, patents, business plans, etc.). The instructor should spend about twice as much time preparing the guest speaker as the speaker spends with the class.
- Solicit immediate student feedback after guest speakers have visited, and provide candid feedback to speakers expected to return.

IX. ROLE OF NCIIA

Creation of this course was inspired by the 1998 National Collegiate Inventors and Innovators Alliance (NCIIA) conference. NCIIA subsequently funded initial course development and continues to provide a fountain of ideas and resources.

Written communication is an important skill for budding entrepreneurs. Four teams submitted E-Team proposals to the NCIIA requesting up to $20,000 each in continued funding; three were successful. The funded teams work through the summer to iterate their designs, refine their products and explore patent possibilities.

X. CONCLUSION

An underlying philosophy of the ITL Program is that "engineering is about creating ideas and products that benefit society." Coupling hands-on product invention with real-world considerations (such as manufacturability and profitability) is an excellent way to underscore this point. Accompanying student groups on their journey to becoming productive teams is a challenging and rewarding voyage furthered by creating a classroom environment that sets the stage for risk taking, supports failure, and rewards candid and productive feedback. The resulting high-quality and creative products developed by successful teams make it worth all of the work!

REFERENCES