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Fostering Innovation in Cornerstone Design Courses*

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The boundaries between engineering design and business are becoming increasingly blurred and the need to produce innovative, entrepreneurial engineering students is growing. This work explores the meaning of innovation and how innovation is currently included in undergraduate curricula. It presents an 8 element model for encouraging innovation in cornerstone design courses based on a required cornerstone design course at the Korea Advanced Institute of Science and Technology (KAIST). The difficulty in measuring innovation in student design projects is discussed, the limitations of proxies for innovation such as patents and publications are demonstrated, and the impact of national and disciplinary culture on innovation proxies is examined. The challenges and limitations in continuing design projects after the end of the semester and for incubating technology developed during the semester at KAIST are described and a follow-up course on innovation and entrepreneurship is proposed.

Keywords: engineering design; first year; education; innovation; entrepreneurship

1. Introduction

Innovation is seen as an engine for large scale economic growth. As a result, a growing emphasis on innovation can be found in all sectors. The need to foster innovation is reflected in national policies to promote science and technology [1], government investment in new technology ventures [2], and calls both from the government to address 'the shortage of people with the skills and knowledge to make innovation happen' and from industry to improve 'academia's coverage of creativity methods' and increase the number of individual and interdisciplinary design projects being offered [3]. As a result, engineering design educators are increasingly interested in how to include, encourage, and measure innovation in their courses and curricula.

This paper discusses the benefits and challenges in encouraging innovation in cornerstone design courses like the KAIST Freshman Design Program. In the first part of the paper, a number of definitions related to innovation are presented, examples of courses which were specifically developed to promote innovation and entrepreneurship in undergraduate engineering majors are shown, and the suitability of innovative conceptual design as a topic for cornerstone design projects is discussed. The second part of the paper provides an overview of the KAIST Freshman Design Course (FDC), including its general format and the steps taken to encourage innovation in student projects, and presents 8 elements which could be incorporated into general cornerstone design courses to increase innovation. In the third part of the paper, the difficulty in measuring innovation in student design projects is discussed and the limitations of proxies for innovation such as patents and publications are demonstrated. In addition, the challenges and limitations in continuing design projects after the end of the semester and for incubating technology developed during the semester at KAIST are described. Finally, a follow-up course on entrepreneurship and innovation is proposed to improve support for successful design projects and encourage innovation and entrepreneurship activities at KAIST and in Korea.

2. Defining innovation

Although the importance of innovation has been well established, a precise definition of innovation remains somewhat elusive. This section provides a brief review of historical and modern definitions and discussions of innovation, invention and entrepreneurship and their relationships, and proposes a working definition of innovation for this paper.

2.1 Historical definition of innovation

The word innovation originally comes from the Latin 'innovare'—'to make new' [4]. In contrast, 'invention' comes from the Latin 'inventus'—'to encounter, come upon, [or to] find' [5]. Thus, the term innovation may have originally been intended to describe a reinvention, interpretation, or re-envisioning of something that already exists for a specific purpose rather than the original act of discovery or creation.

2.2 Modern definitions of innovation

In modern times, the term innovation has been strongly linked to value. Genrich Althsuller, the founder of TRIZ, referred to innovation as a measure of 'inventive value' [6]. Thus, in TRIZ a design that contains something new is an invention,

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while innovation is a scale which measures the (potential or realized) impact of that invention. Thomond and Lettice also view innovation as a continuum which encompasses changes ranging from radical incrementalism to totally disruptive innovations [7]. According to their definition, these changes must precipitate significant transformational change to the market.

Some definitions focus on innovation as a process that creates or enhances value. For example, Marxt and Hacklin say that the term refers to the product development 'process as a whole from establishing a business plan based on strategic considerations to product development and the market introduction' [8]. Here, the value that the process brings to the parent company is implied but not explicitly stated. Kroll et al. are more direct, defining innovation as a process that produces 'novel concepts' and products with 'exceptional functionality' that can 'provide companies with a competitive advantage' [9]. Suh agrees, saying that innovation 'refers to the process of converting research results, ideas, inventions or scientific discoveries into commercially successful products, processes, services or systems' [2].

Dym introduces a third category of definitions which focuses more on the nature of the problem rather than on the nature (or impact) of the solution. He views innovation as an 'intermediate class of designs' between routine and creative design where we possess fundamental physical knowledge but 'lack a clear-cut problem-solving strategy' and the 'knowledge of how, where, and when we should apply [our] fundamental knowledge' [10].

2.3 Characteristics of innovation

One common theme in modern definitions of innovation is an acknowledgement that the value of an innovative design can be in the technical, social, economic, or environmental domain, or in a combination of those domains. Thus, innovation is sought and occurs in multiple disciplines and is often an interdisciplinary undertaking. Hauschildt states that 'innovation is about something new: new products, new processes, new types of contracts, new ways of distribution, market slogans, a new corporate identity,' stressing that '[i]nnovation is more than just a technical problem' [11]. Tura and Harmaakorpi agree saying that 'radical innovations, which are based on advancements in science and technology, are . . . important but they are only one form of innovative activity' [12].

Moreover, there is an increasing understanding that the process of innovation is strongly influenced by techno-socio-economic factors. Tura and Harmaakorpi note that '[n]owadays, innovation is seen to be as much a social as a technical process. Innovations are seen to emerge as non-linear processes deeply embedded in normal social and economic activities, and as processes of interactive learning between firms and their environment'. They go on to say: 'From a regional point of view, innovation is consequently understood as a locally embedded process taking place within the regional innovation environment' which includes 'firms, universities, technology centers and development organizations' and is 'cumulative in nature' [12].

Marxt and Hacklin say that much of the confusion surrounding the definition of innovations stems from the fact that some of the definitions of and terms associated with innovation (like design and product development) originated in business while others come from engineering. They say that innovation initially signified a 'change in business models based on new ideas for creating value, but is nowadays also broadly used for describing change of products or even technological concepts'. They ascribe the blurring of the boundaries between business and engineering and the overlapping lexicon to 'the convergence of technologies, or entire industries' as well as to 'the convergence of processes, the way of developing new products, design and innovations' which have transformed the designer 'into a developer or even an innovator' [8]. This further supports the argument that the potential for innovation is not limited to any domain or discipline and will be enhanced by cooperation across disciplinary borders.

2.4 Design and entrepreneurship in the innovation continuum

Discussions of innovation often coincide with discussions of design and entrepreneurship. In a recent paper, Suh presented a theory of innovation in which he proposed the existence of an 'innovation continuum' and argued that all 12 steps of the innovation continuum must be present in order for innovation to occur [2]. Those steps are:

(1) Identify the need for a new product or process or service or system.
(2) Perform basic and/or background research.
(3) Create, test, select and revise ideas via funneling.
(4) Demonstrate the feasibility of the idea.
(5) Seek intellectual property rights (patents, copyrights, trademarks, etc.).
(6) Test the commercial viability of the idea.
(7) Find an 'angel' who will be willing to invest in steps 4 and 5.
(8) Raise venture capital or find a large company that is willing to take over the idea and develop it.
(9) Create or identify a venture company that can manufacture and sell the product.

(10) Hire talented people for all functions that the company must perform, including R&D, manufacturing, marketing, sales, purchase, and administration.
(11) Raise a large amount of capital through a public offering.
(12) Sell the venture company.

Upon examination, it seems clear that the first six steps in Suh's innovation continuum focus on designing something with a high potential value while the last six steps focus on entrepreneurship which realizes that value (both to the customer and the company) by bringing the design to the market. This implies that innovation is a process that combines design and entrepreneurship by creating and realizing value. However, the steps listed in Suh's innovation continuum are clearly specific to certain types of enterprises, particularly those which involve technological innovations. Social innovations generally do not require venture capital (although they may require other types of support) and are unlikely to support a public offering of stock. Thus, entrepreneurship cannot be an inherent part of innovation. Instead, it accompanies or follows innovation when appropriate. In that case, the innovation must occur in the first half of the continuum which implies that innovation is a type of design.

2.5 Proposal for a working definition of innovation

The working definition of 'design' in the KAIST FDC is a 'human activity which combines resources (knowledge, skills, experiences, creativity, tools, materials, etc.) to meet a need, accomplish a goal, or create an artifact' [13]. Based on this definition and the discussion above, it seems possible to define innovation as a human activity which renews (redefines, redesigns, and/or reinterprets) an artifact (idea, product, service, system, etc.) to meet a need or accomplish a goal, (i.e. to produce value). This definition of innovation (or innovative design) includes both the creation of new designs to address existing needs or goals and the adaptation of existing designs to address new needs or goals. Thus, innovation can be thought of as a type of design activity, distinct from routine design where the result is a tailored version of an existing artifact and creative (or inventive) design where the outcome is totally new. This agrees well with Dym's definition from section 2.2. Based on this definition and the historic definition of invention given in section 2.1, the novelty of an innovation may be lower than an invention but its value may be higher depending on how well it is matched to its intended need or goal. Innovativeness can then be defined as the measure of the (potential or realized) value that is added or created (in one or more domain) because of this activity.

3. Examples of innovation-focused education

The blurring of innovation in business and engineering is evident in courses which specifically focus on teaching or fostering innovation. Most of these programs focus on innovation in the context of entrepreneurship and are offered as upper level interdisciplinary undergraduate electives. For example, Penn State offers an undergraduate minor in engineering entrepreneurship. The program, which is a collaboration among the schools of engineering, business, and information sciences and technology, is aimed at developing students with 'innovative thinking skills'. It also emphasizes team work, communication and presentation skills, and prototyping [14].

Rensselaer Polytechnic Institute offers an interschool undergraduate dual-degree program in product design and innovation. This program is a cooperative effort among faculty in the schools of engineering, architecture, and the humanities and social sciences. In the program, 'the engineering/building science curriculum includes courses in engineering mechanics and electronics, energy, construction, materials, and manufacturing. The [Science, Technology and Society] curriculum covers the social and cultural dimensions of product development and innovation, including case studies of successes and failures' [15].

Brown University offers a two semester undergraduate elective sequence in engineering entrepreneurship which was founded on the basis that emerging technologies and science-based innovations 'have greatly impacted the typical engineering career and also caused a significant shift in employment opportunities for young engineers' which favors entrepreneurial engineers. The program is open to all undergraduate engineering majors [16].

The University of Nevada, Reno offers a special capstone course for electrical engineering and mechanical engineering students which covers all 'phases of new product development including innovation, patent law, product liability, business, sales, marketing and venture capital'. The course, which is also open to MBA students, requires students to 'work as apprentices in a shared space to develop and build prototypes, write patents, and develop business plans'. In the process, students are 'charged with the responsibility of generating product ideas, evaluating and selecting one of the ideas, developing a working prototype, and performing market and financial analyses to determine if the product could sustain an actual business' [17].

Although first year engineering design courses are increasingly common, the only course that I found which specifically focused on invention and innovation for lower level engineering students was at the University of Colorado at Boulder. This course is offered as an elective follow-up to the first year engineering design course. It is intended to cultivate 'an understanding of the entrepreneurship and invention world through a hands-on introduction to product design and development'. The course emphasizes team work, the design process, entrepreneurship, and the market potential of new designs. During the course, the characteristics of 'entrepreneurs, sources of financing, profitability, patenting and intellectual property issues, and marketing considerations are explored' and students in the course 'conduct market surveys to gauge potential sales volumes, as well as what potential consumers are willing to pay for the new products' and patent searches to 'reveal the extent of competition and avoid patent infringement' [18].

4. Innovation in cornerstone design courses

Despite the lack of first year classes specifically devoted to innovation, cornerstone design courses are well suited to innovative conceptual design projects that focus on products, services, or systems.

The syllabus of a cornerstone design course, and thus the nature of the course project(s), is determined by a combination of the desired educational outcomes of the course and the constraints on the teaching team (the length of the semester, the number and type of available resources, the pre-existing knowledge and skills of the students, etc.). First year design courses can be roughly classified into three groups based on their desired outcomes. The first group consists of introduction to engineering courses that focus primarily on teaching engineering skills (machining, drawing, CAD, etc.) in a design context. The second group consists of introduction to design courses that expose students to the design process through a semester-long project. The third group occupies a middle ground, introducing various aspects of engineering and design through a series of small hands-on projects or exercises that often combine analysis (analysis of design concepts and/or reverse engineering) and synthesis. All of these courses must assume that their students will have little or no technical knowledge or skills at the beginning of the semester and must either tailor the projects to work around those constraints or teach the students what they need to know in order to complete their projects.

If the desired focus is design (rather than manufacturing or engineering) and the second type of course is chosen, the course faculty must decide what types of projects are suitable to offer to first year students and what the focus on the project will be. For example, the degree of desired novelty of the design project must be determined. Will the students be asked to produce routine, incremental, innovative, creative designs or radical designs? The target phase(s) of the design process must be chosen. Will the students be asked to focus on conceptual design, system level and the detailed design phases, testing and refinement, or production ramp up? Finally, the scale of the problem to be solved must be chosen. Will students be asked to design components, assemblies, products, services, or systems?

The choices for freshmen are surprisingly few. Incremental design usually expects a small improvement in performance (size, weight, power consumption, etc.). This requires a deep understanding of the detailed mechanisms in the existing design and of the engineering principles which can be used to modify those mechanisms. Both are beyond most freshmen. Similarly, routine design, component and assembly design, and the system level and detailed design phases require knowledge of mechanisms, materials, and engineering fundamentals which are often not available until the junior or senior year. At the other end of the spectrum, creative and radical designs must avoid all solutions that have been proposed before. This places a great burden on the designer, both in terms of benchmarking and background research, and in terms of lateral thinking skills that may not yet be sufficiently developed. Thus, most first year design projects naturally focus on the conceptual design of innovative products, services, or systems, or on trial-and-error type build-and-test projects (Table 1).

5. An example of an innovation-focused cornerstone design course

5.1 Overview of the KAIST Freshman Design Course

The KAIST Freshman Design Course, formally known as ED100: Introduction to Design and

Table 1. Nominal Dimensions of Design Problems

Desired Novelty	Routine	Incremental	Innovative	Creative	Radical
Design Process Phase [23]	Conceptual Design	System Level Design	Detailed Design	Testing and Refinement	Production Ramp Up
Project Scale	Component	Assembly	Product	Service	System

Communication is an example of a cornerstone design course that fosters innovation through a semester-long conceptual design project. The KAIST FDC is not, and was never intended to be, a course on innovation or entrepreneurship. It is a course on the design process, design thinking, and design theory which was developed to help prepare first year undergraduate students to be future leaders. The main goal of ED100 is to produce a 'paradigm shift in the way that its students think, view education, view the world, and view their role in the world' [19]. However, because of the close relationship between engineering design, product design, innovation, and entrepreneurship, ED100 shares many of the goals, strategies, and outcomes with courses which are more strictly focused on innovation.

ED100 is a 3 unit course that is required for all incoming freshmen regardless of major. It was first offered as a pilot course with 29 students in the fall 2007 semester and has been required since the spring 2008 semester. The course is offered twice a year and its average enrollment is 400–600 students per semester. ED100 has approximately 23 sections per semester. Each section has roughly 20 to 30 students organized in 4 to 6 teams with 4 to 6 students each. Sections are led by faculty project advisers (one per section) who choose the general project topic for that section. Projects are not limited to engineering topics and faculty project advisers can come from any department at KAIST. Projects topics from the Spring 2011 semester included:

- Airport Passenger Operations and Security Management (Civil and Environmental Engineering).
- Design of Biofuels from Lignocellulosic Biomass (Chemical and Biomolecular Engineering).
- Design of Educational Games for In-Class Use (Aerospace Engineering).
- Design to Promote Environmental Sustainability (Graduate School of Culture and Technology).
- Discovery of Lighting (Industrial Design).
- Good Packaging, Bad Packaging (Mechanical Engineering).
- iME—Personal Cognitive Assistant (Electrical Engineering).
- Piezoelectric Energy Harvesters (Material Science and Engineering).
- Technology for the Students, by the Students, and of the Students (School of Humanities and Social Sciences).

On the first Thursday of the semester, each faculty project adviser gives a short (2–3 min.) introduction to his or her project. Students then choose their projects and are assigned to a team through the project lottery. Once formed, the student teams refine, and in some cases redefine, the project topic until they have chosen the specific problem that they will attempt to solve. Students can choose to work on different aspects of the same problem or different applications of the same technology. For example, students in the Fall 2009 semester project on user interfaces for ubiquitous IPTV environments designed:

- An IPTV user interface that used augmented reality to guide individuals through airports.
- An interface to aid communication for international disaster relief teams.
- A user interface for IPTVs that could be used by young children.
- An improved method for inputting text on a reduced (10 digit) keypad for IPTV remote controls.
- A system to link IPTVs to major kitchen appliances to permit users to watch TV and monitor dinner at the same time.

During the semester, students are guided through the conceptual design process (problem definition; background and stakeholder research; needs identification; design specification; concept generation; and concept refinement, selection and testing) by attending weekly design lectures (1 hour per week, delivered by the author) and design laboratory sessions (up to 3 hours per week with one of the 23 faculty project advisers). Weekly communication lectures (1 hour per week, delivered by the communication advisers) and communication laboratory sessions (1 hour per week with one of the two communication advisers) or communication clinics (20 minutes by appointment with one of the two communication advisers) are also offered to help students prepare their course deliverables.

Halfway through the semester, students participate in a mid-term design review where they meet with a panel of two ED100 faculty members (design lecturer, communication advisers, and project advisers) and four TAs from other projects. The mid-term design review involves both a written report and an oral presentation with an extended question and answer session. At the end of the semester, each team is expected to produce a written report, a technical poster, and a prototype or other proof of concept materials based on their work. The report describes the students' design problem, design process, and their final design solution. The poster and prototype are presented at the end-of-semester poster fair which is held for four afternoons during the last week of classes. The paper and prototype deliverables are graded by a second panel and the poster and the technical evaluation are graded by a third panel. These panels are referred to as 'grading juries'.

Grading in ED100 is roughly 75% group work and 25% individual work. Students receive individual grades for their design and communication laboratory work. They also receive bonuses or penalties based on their peer reviews, lecture attendance, and course survey participation. The remainder of the grade is based on the group scores for the mid-term and final deliverables. Grading in ED100 is also roughly 75% determined by the grading juries and 25% determined by the faculty project advisers and communication advisers.

5.2 Encouraging innovation in the FDC

Although it is not a course on innovation, innovation is specifically addressed and encouraged in the KAIST FDC. Throughout the semester, the design lectures address topics related to innovation. In the first lecture, students are asked to consider the fact that they, as the future leaders of government, academia, and industry, will be required to solve problems and design systems and solutions (laws, technology, cities, societies) that will be 'new, different, or better' and will make the world a better place. We try to dispel the notion that the students are 'just' freshmen and work to empower them to develop the best designs possible.

During the problem definition lecture, students are encouraged to choose problems that are 'specific, important, manageable, and solution neutral,' ruling out most routine or incremental design problems. They are urged to 'take a step back' and redefine the problem, repeatedly if necessary, until they are confident that they have determined the right problem to solve and have enough leeway to do so rather than simply accepting the problem that is given to them.

In the background and stakeholder research lecture, students learn about literature searches, patent searches, benchmarking, surveys, focus groups, site visits, interviews, and user observations to ensure that students consider the technical, social, and economic aspects of their design problem.

During the design specification stage, students are asked to divide their customer needs and background information into functional requirements, non-functional requirements (or qualities), constraints, and selection criteria. Functional requirements must be organized into a hierarchy with multiple levels of decomposition in accordance with Axiomatic Design Theory [20]. This helps to emphasize functional over physical thinking (i.e. the need to define the right thing to do before considering how to do it) during the early design phases. Physical thinking is actively discouraged for the first six weeks of the semester.

During the concept generation phase, a distinction is made between functional and physical solutions. Examples of bias in failed design solutions that resulted from physical thinking (or a lack of functional thinking) are presented. Students are asked to develop multiple design concepts which are eventually decomposed into hierarchies of design parameters. Different creative design processes (combination, mutation, analogy, first principles and emergence) from Cross's Designerly Ways of Knowing [21] and methods to organize the search for design solutions (morphological charts, concept combination tables, concept classification trees, etc.) from Dym and Little [22] and Ulrich and Eppinger [23] are also presented.

A portion of the solutions and design concepts lecture is devoted to a formal discussion of innovation. Various definitions of innovation, and several taxonomies of innovation, including Altshuller's five levels of technical innovation from TRIZ [4], are presented in order to remind the students to think about innovation and to use it as one of the guiding principles of their work. Near the end of the semester, the students also attend a special lecture on intellectual property by one of KAIST's patent lawyers. During the lecture, students learn about US and Korean patent law and the procedure for filing patents at KAIST. This ensures that all ED100 participants are aware of the possibility of filing patents based on their inventions and know whom to contact if they have questions about the process.

Throughout the semester, students are also encouraged to think about the long term potential for their design projects. In the first lecture, students are told that their predecessors' projects have resulted in patents, conference papers, and journal publications. They are urged to consider following in those footsteps and focus on where their project might go instead of the grades that they will receive at the end of the semester.

At the end of the semester, the innovativeness of the students' project is evaluated as part of the technical evaluation. The technical evaluation (worth 20% of the final grade) focuses on the students' design problem, process, and results. One of the criteria from the technical evaluation asks if 'the importance of the problem/need for the solution was clear'. Others ask if 'the resulting design is new/different/better/interesting' and if 'the novelty of the design was well explained'. These are only 3 criteria out of 19 and thus do not have a substantial impact on the final grade. They are present primarily as a reminder to both the students and the faculty to consider innovation during the course and its evaluation.

Similarly, students are required to produce a prototype or some type of proof of concept (PPoC)—customer testing, technical testing, experiments, calculations, simulations, technical references, etc.—to prove that their solution is feasible and will be technically, socially, and/or economically successful. However, the PPoC evaluation sheet contains only one criterion that explicitly addresses this: 'I believe that the final design will be successful'. All of the other criteria focus on the questions that PPoC were intended to address, if and how those questions were answered, and whether or not the methods and results met the expectation of the grader. As a result, innovation is a constant theme throughout the semester but is not strictly defined and not required to receive a high grade in the course.

6. Factors for fostering innovation in cornerstone design courses

Although all of the elements described above have an impact on the innovativeness of ED100 student projects, they can be roughly classified into 8 basic factors which could be transferred to other courses:

- The freedom to choose (and/or refine) the project topic.
- A distinction between functional and physical thinking.
- Formalizations in the design process to focus and structure thinking and force meaningful reflection.
- Self-directed learning.
- A techno-socio-economic (rather than purely technical) focus.
- The elimination of 'professor-pleasing' design strategies using jury-based (or expert based) grading.
- A large-scale, team-based model that encourages peer learning and the development of institutional knowledge about the course.
- Motivation and buy-in from the course students and faculty.

6.1 Freedom to choose (and/or refine) the project topic

One of the great strengths of the KAIST Freshman Design Course and the most important factor in fostering innovation in cornerstone design projects is almost unlimited choice of project topic. It was previously shown that the freedom of project choice in ED100 makes the course more nimble and better able to respond to trends in research and industry [24]. Allowing the faculty members to choose their project topics makes it possible to recruit the large number of project advisers needed each semester. And allowing the students to re-direct their projects increases satisfaction and buy-in. But more importantly, innovation requires a re-envisioning or a re-interpretation of existing ideas or artifacts that may ultimately fall far outside of the original bounds of the problem. If the students are not permitted (or, in this case, required) to re-examine, re-direct, and reframe their design problems, they become bound by unnecessary constraints which reduce the solution space may prevent them from being able to develop innovative ideas.

There are several additional dangers associated with restricting project topics. It is very easy to (accidentally) define a design problem where most of the major conceptual design decisions have already been made, leaving only the detailed design and build-and-test for the students. This changes the focus of the course from conceptual design to engineering (design) and greatly restricts the ability of the students to innovate. In ED100, all project topics proposed by the faculty must be approved by the course director to ensure that they are problems to solve or more general themes to consider rather than artifacts to build.

Next, the lack of ability to transform the project topic into something accessible and manageable can lead students to feel like the given design problem is trivial, contrived, or otherwise 'not real' and can lead to design projects that are little more than thought experiments. This decreases student learning and student satisfaction with the course, and can cause the students to stop taking the course seriously or stop working on their projects altogether.

Finally, requiring the students to have their design problems 'approved' by their faculty advisers can lead to a situation where the students feel like they are being forced to guess what their professor wants them to work on rather than being responsible for the choice. In ED100, students must justify their choice of problem but they do not need their project adviser's approval to pursue it. Project topics are never locked in. Design problems can, and do, change mid-semester as students realize that their original direction is not as promising as it seemed and that a new approach is needed. Some design projects change focus as little as one week before the poster fair due to discoveries during prototyping. These teams must scramble to re-do many of the homework assignments for inclusion in the final paper, but this decision still usually results in a much better project.

Students in ED100 do not have unlimited choice of design problems. Their project must be related to the topic defined by their project adviser (although the relationship is sometimes tangential at best). Students are given guidelines for choosing project topics. For example, they are repeatedly urged to choose problems that are 'important, manageable, and solution neutral' that will result in solutions that are 'new, different, or better'. However, the students seem to be naturally motivated to choose these types of problems and strive for innovation solutions. They need very little prompting. Finally, specific grading criteria are provided for each homework assignment and for the mid-term and final deliverables. These are very important for the course faculty and staff who use them to guide their feedback to the students and to maintain the consistency of grades produced by the grading juries. But in general, the grading criteria seem to have a relatively small impact on the students themselves. They (correctly) assume that good work will be rewarded and try to focus on the design task rather than its evaluation.

6.2 Distinguishing between functional and physical thinking

One of the hallmarks of good design thinking and one of the founding principles of Axiomatic Design Theory is the distinction between functional thinking and physical thinking. Functional thinking requires designers to consider what they want to achieve (or what functions they wish the design to perform) independently from (and usually before) how they will (or what physical mechanisms they will use to) achieve it [20]. This is the difference between stating 'I need a spoon' (a physical object) and 'I need to stir a pot of soup' (a function which can be performed with any number of physical objects) [13]. Most people are very proficient in and default to physical thinking. However, this can lead to bias in design solutions (easily seen in the prevalence of early feather-and-wing-based concepts for flying machines) and prevent the development of innovative ideas.

Before the beginning of the semester, ED100 students are aware that they need to 'think outside of the box' but few know how to do so. We believe that distinguishing between functional and physical thinking, showing students numerous examples of how these concepts apply to real products, and demonstrating how a failure to understand the difference can (and has) lead to design failures causes the students to start questioning all of their previous assumptions. This, in turn, helps the students to take a huge step away from 'the box' and opens up limitless possibilities for innovative designs.

The process of learning to think functionally is challenging for students and professors alike, and students in the KAIST FDC do struggle in the beginning. But we find that first year students adapt to this and other aspects of design thinking much more readily than similarly inexperienced graduate students. Thus, we do not believe that delaying the introduction of design thinking until upper or graduate level design courses is beneficial for the students.

6.3 Formalizations to focus and structure thinking and force meaningful reflection

A common criticism of formal design theories and methodologies is that they increase the workload of the designer while restricting his or her creativity. However, in ED100 we find that formalizations in the design process help students to focus, organize, and structure their thinking and take the course and their projects more seriously. The assignments in ED100 force students to view their work more objectively, prompt meaningful reflection on their design process and products, and ultimately result in more innovative outcomes.

The design lectures themselves probably have very little effect on the innovativeness of student projects. In order for reflection to occur, the students must be required to apply the lecture material to their projects in a meaningful way. All too often, students in design courses sense the presence of a divide between the lectures and the project or realize that they will be evaluated solely on their final outcome and not on their design process. As a result, they either skip the homework entirely or treat it as busy work. This is not the case in ED100. Not only is the final design concept only a small portion (5%) of the final grade, the homework assignments based on the design lectures are the basis for the mid-term (10%) and final (20%) reports. Thus, there is no way to avoid (re)doing them or taking them seriously.

This does not imply that the use of formal design theories, like Axiomatic Design, guarantee an innovative design. We have many teams in ED100 which do an outstanding job with the design process and design theory but do not develop truly innovative ideas. Nor does it imply that innovation cannot occur without the use of formal design theories. We also have many teams in ED100 which produce innovative ideas with little theoretical basis. It is merely an acknowledgement that providing a formal structure with a strong theoretical basis seems to greatly increase the overall quality of the student projects in the KAIST FDC and the innovativeness of the ideas produced by the student teams.

6.4 Self-directed learning

Self-directed learning is a necessary part of background and stakeholder research and thus is a common feature in design education. However, because teams in ED100 are working on very different projects, the degree to which each team is responsible for the details of their design processes is much greater than usual. For example, when performing background and stakeholder research, students must choose which combination of literature searches, patent searches, benchmarking, expert interviews, user observations, focus groups, surveys, site visits or other activities they wish to perform. They then have to identify the experts or users, make appointments, draft agendas, conduct and document their meetings on their own. Similarly, for the prototype and proof of concept activities, students must choose whether to focus on the technical, social or economic aspects of the project and then decide which methods (prototyping, customer testing, technical testing, experiments, calculations, simulations, and technical references) will best demonstrate their project's potential based on the skills of the group members, the resources available through the project adviser and so on.

ED100 students report that the most difficult parts of their homework are (1) determining what the assignment is asking for, (2) interpreting the assignment in the context of their specific project and (3) making a plan for carrying out the work. Thus, most of their effort goes towards reflection, evaluation, and decision making. Actually completing the assignments usually only takes a few hours per week. We believe that this degree of self-directed learning increases innovation by helping the students to take ownership of their projects while reinforcing the reflection introduced by the formalizations described above.

6.5 A techno-socio-economic focus

In engineering, there is a tendency to view innovation as a purely technical endeavor. However, most schools of 'design thinking' today encourage the treatment of design as a techno-socio-economic undertaking. Similarly, most of the definitions of innovation, including those from Hauschildt [11] and Tura and Harmaakorpi [12] above, note that innovation is a techno-socio-economic activity and the value created by the renewal of the design can be in any or all of these domains. We believe that emphasizing the interdisciplinary nature of design is an important factor in the development of innovative student projects. The success of this philosophy is evident in the fact that the contributions of KAIST freshman design projects consistently appear in all three of these domains. Some of the more sophisticated projects span two or more of these domains.

6.6 Eliminating professor-pleasing via expert or jury-based grading

Because design courses are graded, there is a tendency, particularly for students who are uncomfortable or unfamiliar with solving open-ended problems, to try to convince the professor (customer, client, teaching assistant, etc.) to provide the 'right' answer to the design problem rather than trying to solve the problem on their own. In courses where each section is graded by the faculty adviser, it can be difficult to provide feedback to the students without the risk that it will be viewed as an instruction rather a suggestion. However, in ED100 the faculty project advisers grade each other's projects through randomized grading juries. It is impossible to predict which professors must be pleased a priori, leaving the students with no choice but to produce the best design that they can. The same effect can be accomplished in a smaller design course by having all of the projects from all of the sections evaluated by a single panel of jurors made up of the most experienced faculty members in the course, outside design experts, or a combination of the two.

The ED100 grading system is explained in detail at the beginning of the semester and again at various times during the semester. However, it is a complicated system and admittedly many students do not take the time to fully understand how they are being evaluated in the course. Without this understanding, it might seem like a jury-based grading system would not act as a deterrent to professor-pleasing behavior. But even if the students do not understand the grading system, the course faculty members do. This understanding influences the way that they advise their students and provide feedback about their projects and accomplishes the same result.

6.7 Large scale, team-based courses develop institutional knowledge and promote peer learning

In education, smaller courses with a better faculty-to-student ratio are usually preferred. However, in ED100 we have found that size is an advantage. During the past three and a half years, over 3,000 students have participated in the KAIST Freshman Design Course. This means that it is very easy to find classmates and upperclassmen who have taken the course and can answer questions, give advice, interpret assignments, and share example documents. Over time, institutional knowledge about the course and an informal support network have developed that greatly reduce the anxiety of current students and allow them to concentrate on developing innovative designs.

There are, of course, ideal numbers of students per team and teams per faculty member. In ED100, we have found that the course workload is too great for teams of 3 or less and that teams of 7 or more tend to fragment rather than work as a group. Teams of 4 to 5 students are ideal. More importantly, we have found that 3 teams per section or less produce too little variation within the section. This reduces in-class discussion, cross-team learning, and the quality of the final projects. 7 teams per section or more overwhelms the faculty project adviser, even if more teaching assistants are provided. Thus, we have set a limit of 4 to 6 teams per section in ED100. In general, too few teams per section results in much worse project quality than too many, indicating that students are learning from each other at least as much as they are from the course faculty.

There is one final benefit associated with the size of ED100. At the end of the semester, students exhibit their work (ideas, prototypes, and optional concept videos) at the end-of-semester poster fair. While this creates a celebratory environment for the students to share their work and an opportunity for the members of the grading juries to grade the posters and prototypes, it also creates one final learning opportunity. It shows all of the students in the course what they were expected to do, even if they had not done it. Thus, the inter-team learning that usually occurs within each of the sections extends across the entire course. We find that students do not fully appreciate the course until the poster fair.

6.8 Motivation and buy-in

Finally, many of the course elements (lectures, prizes, etc.) focus on increasing student motivation and buy-in. Although this seems to be less of an issue in the US, Korean students do not automatically understand or value design education. Students rely on their professors, their parents, and their peers to help determine the importance of the FDC and thus the amount of effort that should go into it. Unfortunately, ED100 is a high profile course and to some extent its image is outside of our control. During semesters when there was public disagreement about the value of the course, the overall quality of projects was poor and the level of innovation was low. In contrast, when public opinion of the course was high, student motivation and buy-in were also high and the results of the student projects were outstanding. Thus, we believe that student motivation and buy-in are critical factors in fostering innovation in cornerstone design courses.

7. Measuring innovation in an educational context

Innovation in an educational context is very difficult to measure. Clausing and Fey argue that ''innovation performance is measured by the number of new ideas per year, the hit rate of those ideas, the value to the customer of each successful idea, and the cost associated with the innovation, including the cost of development' [25]. However, none of those metrics are measurable in an educational setting.

Design projects often include creativity or innovation as one of the criteria for judging [18, 26]. However, student grades in project-based courses like ED100 are not solely (or even primarily) based on the quality of the final product or solution. At KAIST, grades are strongly influenced by the amount of effort that the students put into the project, the students' writing and communication skills, the students' understanding and mastery of engineering design processes and theories, and the quality of their prototype or proof of concept. Students who do excellent work, even if it is not innovative work, can still receive top marks. Similarly, at the University of Colorado, Boulder, 70% of the students' grades are based on factors like their 'design review presentations, overall product quality and completeness, and thoroughness of the business analysis and feasibility study' [18]. Thus, grades are not a good indicator of the level of innovation produced by students in a course.

Many courses, including ED100, give a prize or a series of prizes to recognize outstanding student achievements. In ED100, this includes a prize for outstanding creativity and innovation. However, such awards are subjective and based on the judgment of the individual(s) who must make the decision. A design that delights, excites, or inspires a judge or a design that fulfills one of the judge's previously unidentified or unfulfilled needs is certainly one that has innovative potential. But a single judge can only ever serve as a single data point. For true innovation, the market, composed of countless individuals, must be the judge.

Many design and entrepreneurship courses and competitions try to minimize this subjectivity by employing expert judges to determine grades and awards. For example, at Penn State judges 'are drawn from local industry, small start-up technology companies, venture capitalists, and business development staff' [14]. At the University of Nevada, Reno, 'a panel of practicing engineers judges all student projects' [17]. Of course, the problem of the single (or finite) source(s) of feedback remains. But this problem cannot be overcome unless the student projects obtain venture capital funding and go to market.

The best indicators of innovativeness (i.e. potential for success in the market) which remain available to us are those that indicate a belief in the idea and a willingness to continue to devote time and effort to it. In ED100, these are the same indicators of research success in an academic setting: the continuation of the project through the undergraduate research program, filing patents, writing conference and journal papers, etc. Since the course began in the fall of 2007, students and faculty members in ED100 have filed 23 patent applications based on work done in ED100. One of the patents from the spring 2008 semester was awarded last

Table 2. Outcomes Associated with KAIST Freshman Design Projects since Fall 2007

Korean Patent Applications from the FDC	23 Submitted
Patents Granted from the FDC	1 Granted
International Journal Papers from the FDC	2 Published
Conference Papers from the FDC	8 Published
Invited Talks from the FDC	3 International, 9 Domestic Invited Talks
Domestic Design Exhibitions from the FDC	1 Exhibition

year. ED100 students and faculty members have also published 2 journal papers and 8 international conference papers about their work. One of those teams won an award for best student presentation and another received an honorable mention for best paper. An additional 3 teams made conference presentations that were not accompanied by full papers. Nine teams were invited to present their work at an invitational event sponsored by Samsung Electronics. And one team exhibited their work at the 2009 Korean Design Expo. Finally, we know of three teams who have chosen to continue working on their ED100 projects through the Undergraduate Research Participation program. The known results from ED100 are summarized in Table 2. Due to the difficulty in tracking the outcomes of such a large course, these results may be incomplete.

8. The limitations of proxies for innovation

We are very pleased with—and occasionally very impressed by—our students' work. However, the statistics are potentially misleading. Both journal papers, two of the conference papers, the design exposition exhibit, and 8 of the patents all came from the same project. The driving force behind that work was one excellent (Brazilian) student and one excellent (American) project adviser. Only seven project advisers have helped their students to file patents based on their work in ED100. Of those seven, only four of them are from technical disciplines. The other three are from the Industrial Design Department (2) and the School of Humanities (1). Only two faculty members have helped ED100 students to publish their work in conferences or journals. Both are American. This indicates that comfort and familiarity with innovation are influenced by both national and disciplinary culture.

The intellectual property (IP) policies of the school play a role in these outcomes. Students cannot file patents on their own. They must have the help and support of a faculty member. (The faculty member is not required to accept any of the royalties from a successful patent if they do not believe that they contributed to the work.) In addition, filing a utility patent in Korea can be done at KAIST free of charge. However, international patents, while less expensive to file than in the United States, are not supported and must be paid for by the students or the faculty adviser's research budget. Thus, the barriers to filing student patents at KAIST are both higher and lower than at other institutions.

It seems that four things must be present for an ED100 project to continue. First, the project must be of sufficient quality (sufficiently innovative) to justify continuing. Second, the faculty project adviser must be willing to advise the students in how to move the project forward. Third, the faculty project adviser must be able to advise the students as their work progresses. And finally, the students must be willing to continue their work.

In ED100, the first and second seem to be relatively easy to accomplish. Each semester, there are a handful of projects with what appear to be genuinely innovative ideas. In addition, we have outstanding and enthusiastic faculty members who genuinely care about their students. The fourth criterion is a little more difficult. Students at KAIST are very busy and often intimidated by the kind of self-directed learning that is needed for research and development activities. However, the third criterion is the most difficult to meet by far. Some faculty members may be dissuaded from helping their students continue their projects because of a lack of time, but most are held back by a lack of experience in filing patents and incubating technology. When approached about filing a patent about a particularly good student project from his section, one project adviser replied: 'Frankly speaking, I usually do not file the patent in my works but publish them in good journal. I do not know much the patenting process, so that it is very difficult for me to help the students to do the process'. The students were too afraid to do the work alone so the project was abandoned.

Part of this problem stems from the fact that ED100 is a very large program that welcomes participation from all interested parties. The Penn State engineering entrepreneurship program (E-SHIP) boasts that '[s]eventy-five percent of the tenured and tenure-track engineering professors . . . who teach E-SHIP Minor core courses either have patents or have experience in technology-based venture creation' and that all 'of the other non-tenure track faculty . . . either have high-tech start-up experience, work in technology transfer, or

Table 3. Historical Participation in the KAIST FDC by Semester. The number of projects per semester was capped at 23 in Fall 2010

	Projects Offered	Depts. Involved	Project Advisers	Comm. Advisers	Head TAs	Project TAs	Comm. TAs	Moodle TAs	Students
Fall 2011	21*	11	21	2	2	42	4	2	484
Spring 2011	22*	13	22	2	3	44	4	2	434
Fall 2010	23*	12	24	2	3	47	4	2	507
Spring 2010	28	15	30	2	3	59	4	4	481
Fall 2009	17	13	17	2	2	34	4	2	601
Spring 2009	19	14	19	2	2	38	4	2	378
Fall 2008	17	13	19	4	2	34	4	2	368
Spring 2008	20	9	20	2	2	24	0	4	392
Total	167	19	102	7	13	237	19	13	3645

are doing research involving next-generation technologies' [14]. But only 10 individuals are included in those statistics. In contrast, ED100 has hosted 102 different faculty project advisers from 19 departments since the spring 2008 semester (Table 3). This is roughly 18% of the tenure track faculty members at KAIST. Of those, 32 professors (31%) have participated more than once. In any given semester, only 40–50% of the faculty project advisers participated in previous semesters.

At the same time, the variety of faculty participation is one of the course's strengths. Most faculty members at KAIST did not have the opportunity to take courses like ED100 when they were students. Thus, participating in the course is both an opportunity to teach design and an opportunity to learn. In an interview for a short video about ED100, one senior faculty member said 'Actually, I needed this kind of course because I started a venture in 1999. But if I had taken this course before, my approach to solving that problem could have been different'. Another faculty project adviser described ED100 as a 'wonderful and new experience [for] all freshman and also me'.

ED100 teaching assistants have made similar observations. In another interview, an ED100 TA said that her students often proposed problems or solutions which she had never considered and so she was 'very surprised about their thinking' and also learned from the FDC. She continued, saying 'I think that freshman design course is [a] very good opportunity and challenge for [the] student[s] and at the same time for the design teaching assistants'. Another TA echoed the same sentiment, saying: 'As a project TA, actually my role is to guide the students but sometimes I feel like I'm learning with them because they've got very different ideas than me'.

Although the exposure of the faculty and graduate student population to engineering design thinking is not the primary goal of ED100, there was always a hope that the course would have a larger impact on the KAIST community. There is evidence that this impact is occurring. The KAIST Electrical Engineering (EE) Department recently requested the privilege of hosting 10 freshman design projects per semester. At KAIST, freshmen do not choose a major until their sophomore year so we initially assumed that the EE department wanted to use the FDC as a recruitment vehicle. Instead, the EE department wishes to use the FDC as a training mechanism. The electrical engineering department is very interested in educational innovation and wishes to offer more open-ended, creative, and project-based courses. They believe that a greater familiarity with the FDC will aid their faculty members in developing and offering these courses and thus wants to ensure that each EE faculty member has a chance to participate in ED100 in the early days of the initiative. In this case, a relatively low (30%) rate of repeat project advisers is not an indication of failure but rather of success. When the faculty members have learned what the course has to offer, they can return to their departments to develop design and innovation-focused courses of their own.

The commitment of KAIST EE Department is a genuine and exciting indication of educational innovation in the FDC. But how to accurately evaluate the innovativeness of student projects in the course remains an open question.

9. Extending and supporting innovative cornerstone design courses

It has been shown that ED100 shares many features with courses which are specifically targeted at innovation and entrepreneurship including an emphasis on team work and communication, interdisciplinary themes, techno-socio-economic perspectives, a stakeholder-centered approach, and a desire for prototypes and/or proof of concept. However, there are major differences as well. ED100 does not address marketing, the venture capital process, how to write a business plan, etc.

When we examine ED100 in this context, it is clear that the course only covers the first 6 steps of Suh's innovation continuum [2] while many of the courses described at the beginning of the paper either focus on the last 6 steps, or they cover all 12 steps in less detail. If ED100 has difficulty in helping students to identify and incubate promising technologies, then perhaps it is because both the students and the faculty have little or no knowledge about the second half of the innovation continuum and we have been unable to provide them with support from individuals who do. In this case, a second course (ED200: Introduction to Innovation and Entrepreneurship) might help to support and incubate the promising technologies developed in ED100.

All of the examples of courses in innovation and entrepreneurship presented at the beginning of this paper are elective courses. A first year elective in innovation and entrepreneurship would be a valuable addition to KAIST. However, we have shown that because ED100 is a required core course, it benefits the freshmen and the faculty and staff members involved. Creating a required core course (or a large scale elective) in innovation and entrepreneurship would not only educate the students and encourage them to pursue these types of endeavors, it would also help to educate the faculty and graduate population, help them to develop and incubate technologies related to their research, and encourage them to start new companies in the future.

Requiring every first year student to learn about innovation and entrepreneurship could also have an impact beyond KAIST. A recent article in the Globalist [27] addressed 'the lack of an entrepreneurial culture' in Korea 'particularly among Korea's youth' and noted that despite 'the country's recent policy moves to make itself more hospitable to entrepreneurs, . . . this issue needs to be addressed if the country's economic development is to be sustained'. Introducing a freshman core course in innovation and entrepreneurship could dramatically increase the comfort and familiarity of Korea's future scientific and technological leaders with innovation and entrepreneurship activities and help to establish an entrepreneurial culture in Korea.

10. Conclusions

The boundaries between business and engineering are beginning to blur, bringing the worlds of engineering design, product design, innovation and entrepreneurship together. A number of universities have developed undergraduate elective courses to prepare engineering students to compete in a more entrepreneurial world but very few of these options are aimed at first year students. Despite this, cornerstone design courses seem best suited to innovative conceptual design projects because of the limited backgrounds of first year students.

Although the KAIST Freshman Design Course was developed to teach students design thinking and to prepare them to be future leaders in science and technology, it also introduces and encourages innovative thinking and may be a good model for fostering innovation in cornerstone design courses. This work has presented a brief overview of the KAIST FDC along with a description of the ways in which innovation is encouraged in the course. In addition, it has identified 8 factors which seem to have the greatest impact on the innovativeness of student projects and could be used in other cornerstone design courses:

- The freedom to choose (and/or refine) the project topic.
- A distinction between functional and physical thinking.
- Formalizations in the design process to focus and structure thinking and force meaningful reflection.
- Self-directed learning.
- A techno-socio-economic (rather than purely technical) focus.
- The elimination of 'professor-pleasing' design strategies using jury-based (or expert based) grading.
- A large-scale, team-based model that encourages peer learning and the development of institutional knowledge about the course.
- Motivation and buy-in from the course students and faculty.

Innovation is difficult to measure in an educational context because there is no way for the market to react to the students' designs. In addition, proxies for innovation like patents and publications can say more about the background of the faculty project adviser than the quality of the project itself. In order to increase the number of innovation proxies and support promising projects as they enter the entrepreneurial phase of their development, it may be helpful to follow innovative cornerstone design courses with a course on innovation and entrepreneurship. A large scale follow up course at KAIST could help incubate FDC student projects, teach the larger KAIST community about innovation and entrepreneurship, and help to establish a culture of innovation and entrepreneurship at KAIST and in Korea.

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