Creative Thinking in Engineering Education:
Lessons from Students at the Massachusetts Institute of Technology

By

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SUBMITTED TO THE ENGINEERING SYSTEMS DIVISION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

Engineers have deemed creative thinking a necessary skill in their line of work, and ABET, the accreditation board for engineering schools, can evaluate a program based on how it attempts to teach it in its courses. And yet, many students and professors feel that creative thinking is a skill often overlooked by the traditional engineering curriculum. This thesis investigates student acquisition of creative thinking skills in four engineering design courses taught under the Mechanical Engineering and the Aeronautics/Astronautics Departments at the Massachusetts Institute of Technology. Quantitative research methods (surveys, assessments) and qualitative methods (interviews, focus groups) are combined to identify factors that influence student creativity in the classroom and retention and use of creative thinking skills beyond the classroom. Student reflections are used to tie theories of creativity with educational theory on student learning. Common themes discussed by students in relation to creativity include the interactive lecture and lab environments, the involvement of the professors and confidence and hands-on practice. Data shows the relationship between perceptions of team creativity and individual creative development. Recommendations on course structure and supportive institutional policies encouraging creative classroom environments are made based on the experiences of the students and teaching staff of these courses.

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my first group of students. I'm glad I've gotten to see you grow over the years since the class :)

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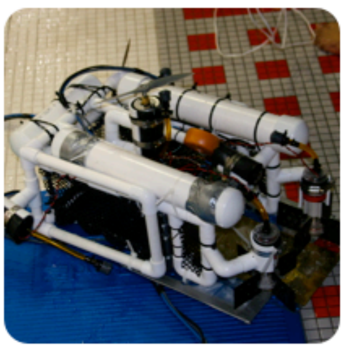

Creative Thinking in Engineering Education

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I. Introduction

Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance.

The Engineer of 2020, National Academies Press (2004)

Creativity is believed to be an underlying driver of innovation; and in turn a factor in the growth and strength of a country's economy. For generations curious scientists, philosophers and individuals have been exploring theories of creativity. Scientists want to know how to define it, managers want to know how to control it and individuals want to know how to improve it in themselves. Progress in scientific research has delineated some of the psychological, social and biological aspects of creativity, yet much remains unknown. When it comes to educating to improve creativity or creative thinking skills, we are only just beginning to look at how instructional methods and pedagogy can influence creative thought in the classroom.

Among the many professions where creativity is valued, engineers have deemed it a necessary quality in their line of work (Klukken 1997; Magee 2004), and it is a criterion on which the accreditation board for engineering schools, can evaluate an engineering program's success (ABET, 2006). The National Academies state that creativity in engineering will be even more important in the twenty-first century (National Academy of Engineering 2004), yet many students and professors feel that creative thinking is a skill often overlooked by the traditional engineering classes (Kazerounian and Foley 2007). In engineering education research, much of the work on students' creativity focuses on outsiders' assessments of creativity and specific processes for students to follow in order to generate creative ideas. It is difficult to determine how to structure classes to best enhance student creativity without knowing what students perceive as influencing their creative thinking skills. At the heart of this thesis is the idea that research on creative thinking in engineering education under-represents the importance of classroom culture and environment as compared to creative thinking processes and activities in the classroom.

This thesis investigates student acquisition of creative thinking skills in engineering design courses at the Massachusetts Institute of Technology through a case study methodology. Both quantitative research methods [surveys, assessments] and qualitative methods [interviews, focus groups] are used to identify factors that influence student creativity in the classroom and retention and use of creative thinking skills beyond the classroom. These student reflections tie theories of creativity with educational theory on student learning, suggesting ways of improving student experiences with creativity in design classes. This thesis is also a reflective piece in that I will examine the role and methodologies used by the teaching team of each course from a insiders perspective. Embedded in my viewpoint is the experience of having been a student within the department that houses the classes examined in this thesis. I will use these different perspectives where appropriate to further describe the context of these classes.

At MIT, there are multiple classes in each department that specifically focus on engineering design. For this thesis, four design courses at MIT were closely examined: *Fundamentals of Engineering Design: Exploring Sea, Space and Earth*; *Solving Real Problems*; *Product Engineering Processes* and *Toy Product Design*. Each of these classes had a specific goal of developing creative thinking skills in their students. They are by no means representative of the majority of design courses at MIT, however each case was found to have lessons that could be applied or transformed for different educational settings. For each of these classes, student data and experiences were collected as well as observations from serving as a teaching assistant in order to understand the administrative and pedagogical aspects of teaching these classes.

All of the classes studied in this thesis were project-based courses focused on teaching design fundamentals through work on a team design and build project. In each class, the end result was a working prototype that could be demonstrated and tested; and in some cases given to a community partner for use at their establishment. A summary of the courses can be found in Table I-1: Courses Examined in this Thesis below.

Table I-1: Courses Examined in this Thesis

	Level of Students	Number of Students	Size of Team	Year Examined	Project Description
Solving Real Problems	Freshmen to Juniors	13	2-6	Spring 2007	Working prototype that can be given to a community partner for their use
Product Engineering Processes	Seniors	100+	14-16	Fall 2007	Alpha level prototype on projects of the team's choosing, fitting into course theme
Fundamentals of Engineering Design	Freshmen	16	3-4	Spring 2007	Underwater ROVs to gather materials in a class competition
Toy Product Design	Freshmen to Seniors	51	2-5	Spring 2008	Alpha level prototype of toy product fitting into course theme

This thesis begins with an overview of research and theories of creativity, in order to explain and contextualize the consideration of creativity within this thesis. The three chapters that follow are each separate case studies of design courses at MIT. The first section, chapter three, is a qualitative case using interviews and focus group data to explore how the students experienced creativity within *Solving Real Problems*. Chapter Four uses surveys and quantitative data to illustrate how students encounter creativity within a senior product design course, *Product Engineering Processes*, at MIT. Chapter Five is a more detailed account of the teaching methods, class requirements and classroom environments of two first-year design courses at MIT: *Fundamentals of Engineering Design* and *Toy Product Design*. It is intended to show a couple of models for teaching creativity in the engineering classroom. Chapter Six is a reflection on the lessons of the thesis and concluding thoughts on what areas of further study might be interesting.

The lessons profiled within this thesis are likely to be of most use to professors and designers of classes who wish to influence student creativity within their classes. However, they also are easily applicable for departments and institutions concerned with creativity; or institutional policy-makers who wish to create environments that nurture and encourage these types of classes.

II. Theories of Creativity and Education

> *On the other hand, a well-functioning community of practice is a good context to explore radically new insights without becoming fools or stuck in some dead end. A history of mutual engagement around a joint enterprise is an ideal context for this kind of leading-edge learning, which requires a strong bond of communal competence along with a deep respect for the particularity of experience. When these conditions are in place, communities of practice are a privileged locus for the **creation of knowledge**.*
>
> Etienne Wenger (1998)

Many individuals have a personal notion of creativity that draws upon their own experiences and observations. This extends to researchers of creativity as well: the act of creation means to bring something new into the world, but should it be new to society or new to the individual who conceived it? How does usefulness factor in? Is it more creative to have a lot of ideas, or a few good ideas? Scientists and society disagree on the answers to these questions, and the schools of thought involved each have equal grounding to assert that their answer should dominate. This section will attempt to clarify the definition of creativity as viewed within this thesis and give it some context as compared to the other definitions in the field.

With regards to educating for creativity, while there has been considerable research on the factors that affect an individual's creative expression, the area of research on developing creative abilities the classroom – particularly engineering classrooms – is still in its formative stage. Researchers differ in opinion on course design, pedagogy and models for professor-student relationships. To further complicate the dissemination of findings, the medium of scientific papers and presentations does not lend itself to communicating the dynamics within the classroom. In this chapter I will go through some of the findings and beliefs regarding educating for creative thinking, including the educational theory that much of this thesis is based upon, lessons in organizational creativity that can be applied in the classroom, and an overview of the literature that is specific to creative thought in engineering education.

The process of a researching and defining creativity

It may seem to be a simple idea in retrospect, but Galton's research on evolutionary diversity is often cited (Albert and Runco 2008) as the beginning of the recognition that creativity comes from within the human mind and our own surroundings rather than from divine inspiration. When society was able to look beyond creativity as a "gift from God" it meant that people could start dissecting creativity into its various environmental and genetic components and look at creativity across several fields as a unified concept. This led to the current research on creativity, which can generally be divided between three categories: the biological, the psychological and the sociological aspects of creativity (Sternberg and Lubart 1999). Biological research includes much of the physiology of how the brain "works" when creating. With the development of functional MRIs this area seen an increase in publication in recent years. In the past this area also considered the genetic inheritance of creativity, but the focus has shifted away from this area of research. Psychological research in creativity also includes consideration of the underlying physiology of creativity in the brain, but focuses more on concepts like behavior, cognition and perception and how they manifest in creative thinking events. The sociological research on creativity is highly tied to the psychological research on creativity; but it instead looks at creative people and creative actions through the lens of environmental factors. This area is where the education and creativity fields overlap: instead of biological or strictly psychological research, education researchers are mostly interested in the social psychology of creativity.

The research on creativity also varies in the type of study subject chosen: processes, individuals, situations, and products, explained in Table II-1 below.

Table II-1: Types of Research Subjects in Creativity Studies

Research Subject	Description
Process	Investigates sequences and patterns of actions that result in creative thought Example: Genrich Atshuller's Theory of Inventor's Problem Solving
Individuals	Investigates lives of people who are labeled creative by society Example: Howard Gardner's *Creating Minds*
Situations	Looks at environments that result in creative thought Example: Mikhail Csikszentmihalyi's Systems Research on Creativity
Products	Looks at objects or ideas that are labeled as creative to discern their origins Example: The Art of Innovation: Lessons in Creativity from IDEO

For educational settings the most applicable types of research are on creative processes, which could be used or taught in the classroom, and creative situations, which could guide how course culture and classroom activities are structured in order to enhance creative thinking processes. Studies about creative individuals and products can help us learn about how items or people that are deemed creative by society have come into being, but often do not have as many direct applications with regards to teaching or developing creative thinking skills in students.

When examining the research in the field, it immediately becomes apparent that there is no agreed-upon universal definition of creativity. In fact, a study by Plucker, Beghetto and Dow

(2004) examined 90 peer-reviewed articles on creativity and found that only 38% explicitly defined creativity. Most definitions include some concept of divergent thinking and ideation. Many, but not all, differentiate between fields and domains: Amabile in particular looks at art, writing and problem-solving separately (Amabile 1996). Some view novelty to society as more important than novelty to the thinker. Still others look at how usefulness factors in. Since there is no single definition for creativity, it is of utmost importance to describe how it is viewed in this thesis. This thesis uses student's self-perceived creativity as the metric for assessing creativity. Rather than defining creativity for the students, I instead spoke to them about how they define creativity in themselves and others, and a collection of these definitions can be found in *Appendix A*. Most of the definitions center on novel and useful idea generation, likely because this is how the topic of creativity was addressed in class lectures.

What do we know about education and creativity?

When thinking about how to enhance creativity in students or in the classroom, the primary considerations are no longer inherent differences in initial creative ability or the biological processes behind creation, but rather how interactions, situations and methods of doing things can affect creative thinking. Sternberg's *Handbook of Creativity* (1999) contains a chapter collecting the research findings on enhancing creativity, but it begins with a caveat: "I confess at the outset that much of what I have to say is speculative. Much of the literature to which I will refer is speculative as well." Sternberg states:

> *I find the following assumptions about creativity to be plausible if not compelling:*
>
> *(1) Both nature and nurture are important determinants of creative expression;*
> *(2) debate over which has the greater effect is generally not very useful;*
> *(3) essentially all people of normal intelligence have the potential to be creative to some degree;*
> *(4) few people realize anything close to their potential in this regard;*
> *(5) creative expression is generally desirable, because it usually contributes positively to the quality of life of the individual who engages in it and often enriches the lives of others as well;*
> *(6) the search for ways to enhance creativity – to help people develop more of their potential – is a reasonable quest in the absence of compelling evidence that such a search is futile;*
> *(7) the evidence, although somewhat tenuous, suggests that creativity can be enhanced; and*
> *(8) how to enhance creativity is not well understood, but there are possibilities that merit exploration.*

Creativity is often thought to be dependent on the interactions between domain-relevant skills, creativity-relevant processes and task motivation (Tighe, Picariello et al. 1983). In this sense, in higher education classrooms students are often learning creativity-relevant processes while practicing and learning domain-relevant skills. As far as the factors that can be controlled or influenced in the classroom that affect creativity, there are a few recommendations in the literature to foster creativity in students.

Many researchers advocate different approaches to creativity based on allowing for open-ended problem-solving (Conwell, Catalano et al. 1993; Blicblau and Steiner 1998; Craft 2006); enabling students to follow multiple solution paths without the constraint of a single right answer. There are also a few problem-solving methodologies that are put forward by educators as means of accessing students' creativity. Brainstorming, or the process of producing several ideas in a short period of time without regard to their use or novelty, is probably the most frequently encountered in the classroom (Baillie and Walker 1998; The Lemelson-MIT Program 2003; Ogot and Okudan 2006). Also common are journals recording all thoughts relevant to a project in order to help the reflection process in learning (Richards 1998; Korgel 2002). Specific to engineering classrooms TRIZ, the theory of inventor's problem-solving, involves breaking a problem into specific attributes and then generating ideas around each of the attributes (Dhillon 2006; Eder 2008). In classrooms that are trying to teach creativity, instructors will usually present one or more of these methods and then encourage their students to apply them in their problem-solving process.

We should consider what factors educators could purposefully manipulate in order to enhance creativity in the classroom. Several studies have shown that intrinsic motivation is a powerful determinant of creativity in tasks (Amabile 1996). However, there are many contextual factors that affect intrinsic motivation either in a positive or a negative manner. Researchers have shown that extrinsic rewards actually decrease intrinsic motivation (Lepper, Greene et al. 1973). These extrinsic influences can include time pressure (Amabile, DeJong et al. 1976, Lepper and Greene 1975), evaluation and even the expectation of evaluation (Amabile 1979). A constant between the various negative influences on intrinsic motivation is the perception of external control over those that are performing the tasks. The positive influences on intrinsic motivation mostly are based on methods of countering this perception of control. For instance, students allowed to choose materials to work with performed more creatively on an artistic task compared to students given a specific set of materials at the onset of the task (Amabile and Gitomer 1984). Along the same lines, studies linking intrinsic motivation and sense of self-determination and competence have shown that greater feelings of competence and opportunities to make choices regarding tasks increases intrinsic motivation as well. Given that many of these factors are common in the classroom, if instructors are looking to enhance intrinsic motivation and thus creativity they must carefully consider how creative tasks are presented and reviewed.

We can also look at creativity in the classroom from an organizational perspective, which is especially relevant for group design classes. This consideration relies on models and definitions of creativity that recognize the situated nature of creation: how creativity is dependent on not only the individuals creating, but also the place, processes and specific product. Csikszentmihalyi's theory, is a fundamentally systems-oriented theory: "What we call creative is never the result of individual action alone; it is the product of three main shaping forces: a set of social institutions, or field, that selects from the variations produced by individuals those that are worth preserving; a stable cultural domain that will preserve and transmit the selected new ideas or forms to the following generation; and finally the individual, who brings about some change in the domain, a change that the field will consider to be creative." (Csikszentmihalyi 1988) diagrammed below in Figure II-1: A Systems Representation of Creativity.

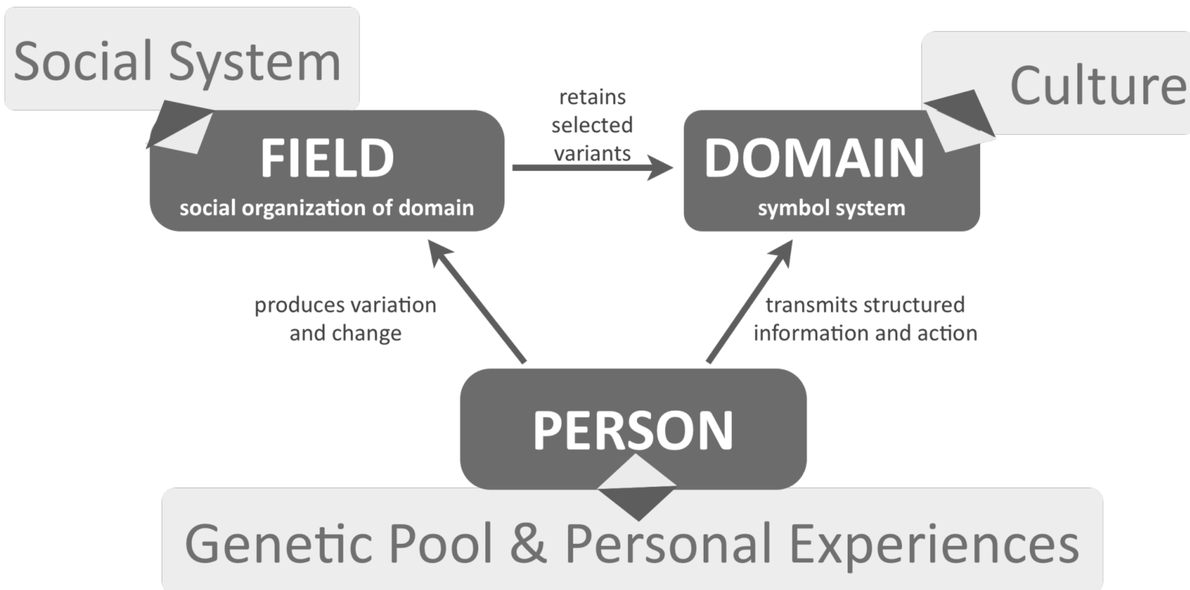


Figure II-1: A Systems Representation of Creativity (Csikszentmihalyi 1988)

Likewise, Plucker et al's definition of creativity acknowledges the situated nature of creativity: "Creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context" (J.A. Plucker, R.A. Beghetto et al. 2004). The first multi-level model of organizational creativity (Woodman, Sawyer et al. 1993) recognized the importance of group norms, social roles, group cohesiveness and problem-solving approaches, providing a theoretical framework to consider creativity in complex social settings. The subsequent research and theory on organizational creativity delineated specific recommendations for group behaviors and leadership in order to enhance creativity. Ford suggests that to support creativity in a group setting, group processes should emphasize diversity of individual skills (Ford 1996). Creative cultures, and cultures where group members feel "safe" have also been addressed as important to individual creativity in a group setting (Agars, Kaufman et al. 2008). As for leadership, close monitoring is seen as inhibiting creativity but developmental feedback can enhance it (Zhou 2003). Group dynamics management through conflict resolution and facilitation of discussions and collaboration are also shown to enhance creativity (Mumford, Scott et al. 2002). The importance of leaders as role models of creative thinking is also brought forward by several researchers (Zhou 2003; Jackson and Sinclair 2006).

Most of these findings are based on studies in the workplace that could have transferability to the classroom. For the most part, these findings have not been tested in academic settings but when considering each finding independently most align with philosophies of teaching. Emphasizing diversity of skills across a group is one way of highlighting the strengths of students in a classroom and help them build confidence in their own abilities. Freeing students from close monitoring to avoid inhibiting their creativity is more complicated since monitoring is central to grading. However, facilitation of discussion and collaboration and teachers as role models of creative thinking are all practices that teachers of creative thinking would engage in the classroom even without research supporting its efficacy.

The Community of Practice theory of learning and creativity

Communities of Practice were first posited by Jean Lave and Etienne Wenger in their 1991 book *Situated Learning: Legitimate Peripheral Participation* and then expanded on in Wenger's follow-up book *Communities of Practice: Learning, Meaning and Identity* (1998). Together these books establish a social theory of learning. They are seminal works in the field of education theory, referenced by thousands and applied in fields as varied as primary school education to large-scale organizational management.

Wenger's "Communities of Practice" are based on the idea that much of learning happens in a social context. This social theory of learning is formed by 4 components:

(1) Meaning: How we as individuals and communities learn how to make sense of and assign significance to our lives and the world around us.

(2) Practice: How social and historical constructs shape how individuals relate to one another, a group of individuals who share a common purpose to society.

(3) Community: How we learn how what is valuable and "worth pursuing" and what society deems as competence in a field.

(4) Identity: How learning changes who we are thus gives us "histories of becoming" in a community.

These ideas are better communicated in diagrammatic form, as in Figure II-2 below.

Figure II-2 Components of a social theory of learning (Wenger 1998)

Three dimensions define Wenger's communities of practice: mutual engagement, joint enterprise and a shared repertoire. Mutual engagement means that the members of community of practice have a direct relationship with one another: "people are engaged in actions whose meanings they negotiate with one another" (Wenger 1998). Wenger stresses that membership in a "community of practice" is not "just a matter of social category, declaring allegiance, belonging to an organization, having a title, or having personal relations with some people." Instead, it has an element of dependence on one another, where the functional relationships complement each other and members are working to complete or perform some "shared practice." The second element, "joint enterprise," is the result of collective negotiation between the members of the "community of practice." It is as much defined by the end product of the negotiation as by the process itself. Through this process of negotiation, members of the community attain a sense of mutual accountability that is important in strengthening the community itself. The final element, "shared repertoire" is a library of "routines, words, tools, ways of doing things, stories, gestures, symbols, genres, actions, or concepts that the community has produced or adopted in the course of its existence and which have become part of its practice" (Wenger 1998).

According to Lave and Wenger these "communities of practice," are present in many aspects of life, however we cannot assume that individuals working together will automatically form a community of practice. There are a variety of areas in which communities of practice can form within the higher education system: within a research laboratory, in the relationships between Masters students, Doctoral students, Post-Docs and Professors; in departments, between senior and junior faculty; between peer groups of students working towards different degree levels; or in classes where students are oriented and working together towards a common goal. Group design courses that require that students work in teams and have individuals with different levels of expertise available as resources to the class are likely places to find communities of practice.

Currently, the literature has yet to draw direct ties between the "community of practice" theory and the literature on creativity. However, there are several connections that can easily be made between the two schools of thought. Csikszentmihalyi's systems-oriented theory of creativity clearly aligns with Lave and Wenger's theory of "Community of Practice." First, *mutual engagement* suggests that meaning is given to individual actions through a negotiation with the individuals that surround are involved in the same practice. Csikszentmihalyi's systems view of creativity clearly articulates the importance of interactions between an individual and society. Furthermore, Csikszentmihalyi's idea of a the cultural domain that preserves and transmits new ideas and forms to the following generation is analogous to Wenger's theory of the transference of knowledge through the interactions between various levels of expertise.

R.J. Sternberg, a cognitive psychologist, has a similar consideration of creativity and intelligence: a three-faceted model that rests on intellect, intellectual styles and personality (Sternberg 1988). He explains each of these three facets using further subcomponents and processes including the ability to recognize the existence of a problem and redefine it to find its solution, acquisition of knowledge and the ability to make sense of information through selective encoding, selective combination and selective comparison. Much of his analysis of intelligence and creativity rests on the idea of experience: through practice and action humans add to their repertoire of methods to consider applying in novel situations. This aligns with "Community of Practice" through the exercise of joint enterprise by the learners – practical experience as a major contributing factor to learning.

Howard Gardner's research on creativity is through a study of historical creative individuals, including Einstein, Picasso and Gandhi (Gardner 1993). His organizing framework for the study of creativity consists of three major themes: developmental perspectives, interactive perspectives and "fruitful asynchrony." Similar to Sternberg's view of creativity, Gardner articulates a theory of "capital of creativity" as a resource that individuals can access later in life. He also suggests that creative individuals retained the "spark of curiosity, possibly because they were strong and rebellious personalities, but even more likely because they encountered at least one role model who did not simply toe the line but rather encouraged a more adventurous stance toward life." These two themes correlate with the ideas of *joint enterprise* and *mutual engagement* – that individuals learn primarily through their interactions with those that surround them and are engaged in the same type of endeavors.

Research specific to creativity in engineering

My initial literature searches during the preparation of this thesis were focused on creativity in engineering. When I broadened my search to include educating for creativity in all fields, it became clear that the general theory on educating for creative thinking differed greatly from the methods and research documented in the literature on engineering education. While many authors cite the necessity for creativity in engineering (Klukken 1997; Brandt 1998; Ihsen and Brandt 1998; Florida 2004; Magee 2004) an overarching vision for creating creative engineers is still absent. Instead the literature is comprised of piecemeal strategies for enhancing creativity. Most studies focus on both individual and team-based design classes. To foster creativity in such classes researchers advocate for the use of design notebooks (Richards 1998; Korgel 2002); lectures on creativity (Richards 1998; Ocon 2006); lectures on common behaviors that block creativity (Richards 1998; Liu and Schonwetter 2004); teaching creative thinking skills like brainstorming, mind mapping and analogical thinking (Liu and Schonwetter 2004); open book exams (Baillie and Walker 1998); as well as many other specific problem-solving processes. Jackson and Sinclair (2006) in their observations of creative expression in higher education recommend an open mentoring relationship between the teachers and the students for developing creativity. Choi's (Choi 2004) work shows that confidence in one's creative skills enhances creative performance. Also, the theory of inventor's problem solving is a common recommendation for engineers (Dhillon 2006; Eder 2008).

However, researchers often speak in generalities about promoting creativity in the classes with out delineating specifically what this means in practice. Kazerounian and Foley (2007) call attention to this fact in their 2007 study of creativity in engineering education. Their paper is one of the few in engineering education that presents a holistic approach to teaching creativity in engineering design courses: a set of maxims of creativity in education. Unlike much of the research in the field that presents items to be included in a checklist of requirements of the students or lecture topics for creative engineering classes, Kazerounian and Foley's work summarizes a philosophy of teaching based on the greater educational theory of creativity meant to promote creativity in the classroom. They delineate some aspects and examples of how these maxims can be applied in an engineering classroom without specifying one correct method for accomplishing each maxim. These maxims are outlined in Table II-2 on the following page.

Table II-2 Maxims of Creativity in Education (Kazerounian and Foley 2007)

Maxims of Creativity in Education (Kazerounian and Foley 2007)
1. Keep an open mind.
2. Ambiguity is good.
3. Iterative process that includes idea incubation.
4. Rewards for creativity.
5. Lead by example.
6. Learning to fail.
7. Encouraging risk.
8. Search for multiple answers.
9. Internal motivation.
10. Ownership of learning.

This list is compiled using the authors' personal beliefs and observations based on their experiences both as students and as teachers; and through a literature review including suggests from domains other than engineering.

Summary

As can be seen from the body of work on creativity, there is quite a bit about the topic that is as of yet unexplored. Amabile's work on intrinsic motivation was the beginning of the recognition that situational factors and context impact creative expression; however much of the engineering education research on creativity still focuses on specific processes and lecture topics to teach creative thinking to students. While brainstorming, ideation, divergent thinking and TRIZ may all have positive effects on student ability to think creatively, there are quite a few contextual and course culture aspects that are as of yet unexplored. The literature shows that these factors are relevant in organizational settings, but these findings have yet to be shown in the undergraduate engineering classroom.

This thesis investigates the role of course culture in students' perceptions of their own creativity in a first-year engineering design course, team factors and time factors in students' perceptions of creativity in a senior design course, and the process of designing and maintaining these types of courses. Using students' perceptions of their own creative thinking skills instead of outward assessments or tests will hopefully lend a fresh and distinct voice to the discussion of how to best inspire and develop creative thinking in undergraduate engineering classes.

III. Cultures of Creativity in the Classroom in *Solving Real Problems*

> *The thing about creativity is that it's something where the potential is always there, but we need to learn how to bring it out. … I feel like [Solving Real Problems] definitely helped me learn how to bring it out: how to say my ideas, how to even think about whether they should be brought out or not. Kind of more express that potential.*
>
> Valerie, first-year physics student

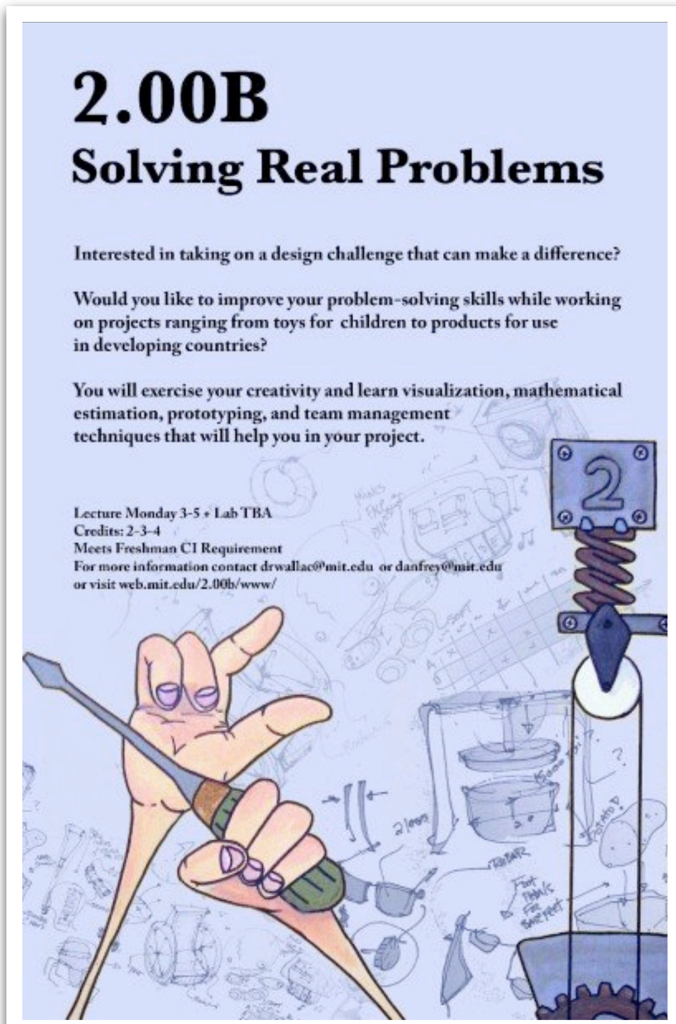


Figure III-1: Recruiting Poster for Solving Real Problems

In the exploration of creativity in undergraduate engineering classes, the viewpoint of the students within the classes is often overlooked. Many, if not most, studies begin with the writer's considerations of creativity and overlook the fact that their study subject's considerations and experiences with creativity may differ from each other and from their own. This chapter looks at creativity in the classroom through the student's eyes.

Solving Real Problems (Wallace 2007) is a first-year level engineering course taught in Spring 2007 under the Mechanical Engineering Department at the Massachusetts Institute of Technology (MIT). In this class, students worked in two to six student teams designing a product of use to local community groups. The community groups presented the class with twelve issue areas within which they could work. Three of these issue areas were selected for further development by the class: a more efficient, larger-scale method of producing compost; a way of making cement that uses a bicycle; a device for helping the elderly read menus in restaurants. The students then went through an ongoing ideation & brainstorming process, identifying key needs of the customers, developing prototypes and building final projects with the input of professors, teaching staff and the community partners. Techniques used during the class included multiple in-class idea generation exercises, individual and group assignments, sketching and fabrication instruction. Amongst other learning objectives, the professors designed the class with the goal of teaching students to generate "creative and workable solutions" to design problems and techniques in order to engage lateral thinking.

As introduced in Chapter Two, Lave and Wenger (1991) first posited communities of practice as an extension of the constructivist concept of learning where learning is student-centric. Their book *Situated Learning* argues that learning is fundamentally a social practice, where those learning are "legitimate peripheral participants" gradually inducted into the knowledge of the larger community. Wenger (1998) expands the "community of practice" model stating that newcomers to a field are inducted to the field's knowledge and skills by the direction and expertise by more experienced individuals. As a 2005 graduate of the Mechanical Engineering program at MIT, I have taken all of the core classes required of the department. My observations as a teaching assistant of *Solving Real Problems* were that it was substantially different from the typical curriculum of the mechanical engineering at MIT; although it was not planned specifically to do so, it invoked the "community of practice" model.

First, this class had thirteen students in total and the teaching style of the professors was to spend much one-on-one time with the students. The class consisted of untraditional lectures in a lecture hall, filled with hands-on exercises where the professors moved throughout the classroom aiding students with their work. Only minimal amounts of time were spent lecturing at the students or teaching with slides or chalkboard-work. The professors also were present during their three-hour evening lab sessions each week working with the teams. The teaching assistants for *Solving Real Problems* also worked with students in lab sessions, assisting them with the machines for building, and providing feedback and advice on their designs. Secondly, students were given open-ended design problems: problems where the professors as well as the students were uncertain about the "best" solution. The learning process was shared between the instructors and the students, although the instructors had more experience in the methodology of the process. The interaction between members and instructors of the class with each other was key in the learning process – feedback was critical to moving potential solutions along and each student, teaching assistant and professor was expected to contribute feedback both to their team and to the other teams of students in the class.

At the end of the semester, eleven of the thirteen students participated in focus groups in which every participant responded affirmatively to the question "Thinking about *Solving Real Problems* in particular, do you think that the class improved your ability to be creative?" It is in this context that I formed the topic explored in this section: *Through the eyes of ten first-year MIT students, how, if at all, did the community of practice within "Solving Real Problems" affect their creative thinking skills?* As with each section of this thesis, it is important to note that this question relies on the students' perceptions of their own creativity (*Appendix A*), rather than outward assessments or tests. The experiences of these ten first-year students are not meant to be representative of all first-year engineering students at MIT, or beyond. Instead, their observations of their experiences in *Solving Real Problems* can be used to illustrate how students perceive and interact with creativity within an engineering class and hopefully inform the design of classes wishing to improve students' creative thinking skills.

Structure of *Solving Real Problems*

Solving Real Problems used a top down approach to teach students about design and engineering. Specifically, this means that the engineering concepts that students learned over the course of the semester were dependent on the projects that students chose to work on at the beginning of the semester rather than lecturing indiscriminately on a broad base of fundamental engineering topics. In the first lecture of the semester students were presented with several projects to choose between for their semester-long design experience. After specific projects were selected by the students, lectures were tailored to the contextual engineering issues needed for work on the chosen projects.

Projects were conceived by community partners and then selected through an application process screened by the professors and the MIT Public Service Center. The projects that the students could choose between are summarized in Table III-1 below.

Table III-1: Projects Available For Selection in *Solving Real Problems*

Project	Community Partner	Selected (Y/N)
Robotic Water Shark	Super Duck Tours	N
Pedal-powered Concrete Mixer	Maya Pedal	Y
Golfer Prosthesis	Therapeutic Recreation Systems	N
Pedal-powered Water Pump	Maya Pedal	N
Vegetable Waste Composter	The Food Project	Y
Reading Device for the Vision Impaired	Partnership for Older Adults	Y
Hands-free Twin Stroller	Vision Impaired Individual	N
Universal Mailbox	Partnership for Older Adults	N
Assistive Swimming Device	Cardinal Cushing School	N

Project selection and work began in the second week of classes. After the presentations of each design project option in the first lecture, each student listed three projects that they would like to work on during the semester. Students were assigned projects based on preference. Thirteen of the fourteen were assigned one of their top three selections. The three projects selected were a composting system for the Boston Food Project, a concrete mixer for Maya Pedal, and a reading device for the Partnership for Older Adults. Teams for each project varied in number and years of experience of student members. The compost team and the concrete team consisted of six and five students respectively. The reading device consisted of three students initially, but only two students by the end of the semester. All students in this class were in their first year of studies except two, who were in their third year. Both third year students were on the compost team. Scenes from the compost team's semester are shown in Figure III-2 on the following page.

Figure III-2: Scenes from *Solving Real Problems* - Compost Team

Thirty students pre-registered to participate in *Solving Real Problems* before the start of the semester; fourteen students showed up to the first lecture and signed up to collaborate on the projects; thirteen students remained in the course at the end of the semester. Though the initial drop of thirty pre-registered students to fourteen attending the first lecture, this is not atypical of MIT's course registration system where students often oversubscribe to courses before the semester begins and then unsubscribe in the first week of class. Of these thirteen students, six were male, and seven were female. Two professors, four teaching assistants, two instructors from the Writing and Humanistic Studies Program and a coordinator from the Public Service Center worked with the students on this course, creating a very low student-instructor ratio of one-and-a-half-to-one.

Students had five hours of class time per week: a two-hour lecture and a three-hour lab section (Table III-2 on the following page). Lecture time was focused on teamwork and general design skills: brainstorming/ideation, sketching for design, materials selection, presentation skills. Importantly, these lectures were peppered with hand-on activities that required students to apply the concepts that they had just been taught immediately. More importantly, there were two professors and four teaching assistants present at each lecture who could mentor and work through applying the concepts with the students. This meant that when students had questions they had someone to turn to and ask immediately. In the student interviews, these informal conversations and one-on-one mentoring time figured prominently in student's memories of the class.

Table III-2: Syllabus for *Solving Real Problems*

Week	Lecture Topic	Lab Topic
1	No lecture – 1st week of class	No lab – 1st week of class
2	Introduction, User-centric design	Design & Build Cardboard Chairs
3	Customer needs, Brainstorming/Creativity	Ideation, Meet the client, Needs assessment
4	Sketching, Drawing for Design	Project ideas compilation
5	Student presentations of project ideas	Machining, Lab safety
6	Teamwork, Ethics, Scheduling	Project work
7	Estimation, Prototyping	Mockup fabrication
8	Presentations to Clients	Part Sourcing, Prototypes
9	Materials selection, Batteries	Prototype fabrication
10	No lecture – Holiday	Prototype fabrication
11	Design detail finalization	Prototype fabrication
12	Effective presentations	Prototype fabrication
13	Presentation Practice	Prototype fabrication
14	Prototype presentation to clients	No lab

Specific engineering concepts such as power transmission elements, part selection, fabrication and design details were taught in laboratory sections by the teaching assistants and professors working with each team. These modules were specific to each team's project, but could be useful for future design projects as well. Client meetings occurred at multiple points during the semester, and students were encouraged to contact their clients whenever they had questions.

Web-based technology was incorporated throughout the *Solving Real Problems* class. A detailed website was used to communicate information about the lectures prior to class meetings, post lecture materials and post the course syllabus. Also, online blogs and wiki-pages were provided to each team. Teams used the blogs to communicate information about the progress of the project to the clients and teaching team, who could then offer suggestions through comments posted to the blog. The wiki-pages were used to disseminate information within teams and were supplemented by team e-mail lists. The web pages, in addition to two mid-semester presentations, were meant to teach students communication skills to fulfill MIT's communications requirement. We found that all teams made use of the web-based blog sites, averaging between one and two posts a week. These posts ranged in length and quality, but overall communicated the status of their design projects well. Some clients and teaching staff used them as a medium to provide feedback to the students, which in turn provided motivation for the teams to use the blog site intelligently. The team wiki-pages were used much less, with only one team posting to their wiki-page during the semester. There are a few potential reasons for the lack of use of the wiki-pages: the learning curve associated with understanding how to post and place files on the sites; team sizes were small enough for face-to-face and other digital communication to be sufficient; team e-mail lists were easy to use and just as effective at sharing files and ideas. Accordingly, e-mail lists were very active and integral to internal communication for each team, as well as student-instructor communication.

At the end of the semester, each team was expected to have developed a full and working mockup of their project to be given to their client. Grading for the semester was shown in the first lecture of the semester and posted on the course website. Certain project milestones did not factor into the grading rubric, namely peer reviews and the initial project ranking assignment to indicate project preference.

Milestone	Percent
Ideation/Brainstorming	10%
Project Ideas	10%
Project Mockup	15%
Progress Report	5%
Presentation Practice	5%
Project Prototypes	25%
Design Journal	20%
Instructor Leverage	10%

Table III-3: Grading Rubric for *Solving Real Problems*

Class Activities for Developing Creativity

Although encouraging creativity was built into the teaching philosophy throughout the entire semester of *Solving Real Problems*, there were a few specific lab and lecture sessions that were targeted directly towards fostering creative thinking in the students in the class. During the first week of lab, the lab activity was a cardboard chair design challenge. Teams of two to three students spent the first half of lab designing a unique conceptual cardboard chair that could sustain the weight of one of the two course instructors. The second half of lab the students passed their design to another team of students, who then build the chair according to the designer's written specifications.

Figure III-3: The Cardboard Chair Design Challenge

An in-lab and in-class activity that required students to ideate, design, build and test structural and unique cardboard chairs in under 3 hours of time.

These chairs were then tested by the instructors during the following lecture which was dedicated to the topic of creativity and customer needs. It was used to highlight ingenuity of engineers over the course of history, as well as to discuss some of the various methods of ideation such as brainstorming and the theory of inventive problem-solving (TRIZ). This lecture section included an in class brainstorming exercise, where students were introduced to a specific brainstorming method of using sheets of paper to capture very quick sketches that convey a specific idea. During the next week of lab students had an opportunity to practice these skills directly, as their customer contacts were invited to participate in a needs assessment with the students followed immediately by a brainstorming session centered on generating ideas for the specific projects that the students had chosen for the semester.

Figure III-4: Brainstorming in Solving Real Problems

At left: Listing customer needs prior to brainstorming session
Right: Categorizing sketches and ideas post-brainstorming session

Case Study Participants and Methods

The participants of this study are the ten first-year MIT students that took *Solving Real Problems (2.00B)* in spring semester 2007, consisting of five females and five males. There were thirteen students total enrolled in the class, two of whom were upperclassmen, one of whom was cross-registered from another university. These three were omitted from the study sample.

In fall 2007, four to five months after students had completed *Solving Real Problems*, I invited via e-mail each of the ten first-year MIT students to sit down and have a 30-minute follow-up discussion about the class. In return, students were offered coffee or other refreshments for their time. All ten students agreed to be interviewed. Interviews took place in various locations on campus based on what was most convenient for the students. Before each interview began I went over the consent form *(Appendix B)* with the participant and asked for permission to digitally record the conversation. The interviews *(Appendix C)* themselves lasted between twelve to twenty-eight minutes and were structured to elicit general commentary about the class before delving into the topic of creativity. Interview times varied depending on the schedule of the students and the amount of time students took to think about questions before responding. However, the shortest interviews sometimes had particularly well-formed responses; it appeared that these two students had thought about the topic of the interview before. Within the topic of creativity itself, I first presented students with open-ended questions and then chose more specific follow-up questions to obtain more detailed responses. The interview protocol was informed by focus groups that were conducted with all of these students at the end of spring semester 2007. These interviews are the core data that is analyzed in this chapter.

After completion of the interviews, I transcribed the conversations verbatim. Using the transcripts, I searched and coded for common themes, first looking within each individual's interviews, and then across individual subjects' responses to the same question. These themes make up the core of the analysis within this chapter.

Analysis of Interviewees' Testimonials

Interactive Environment v. Traditional Classroom

For many of the students, this class was his or her first time working as a member of a team since entering university. Tom characterizes the difference as that working on teams in high school "people kind of look up to the person who has the most ideas and talks the most" whereas "this is more of a group where you're all just equal with everybody else." Five of the ten people interviewed in this study cited learning how to work in a group as a key component of what they have taken from the class. Many students also referenced their interactions with their classmates often in responses to questions about the class influencing their creative skills. Frank states,

> *It was nice having a diverse group. … Of us four freshmen we had a broad range of interests, all of us had these different approaches to things which I think it was very good at bringing out different aspects of design, and what people think is really important…I think it did help the creative concepts because there certainly are things that I wouldn't dare design because from my experience I think they wouldn't work.*

Similarly, Jessica - who was on a separate team - also referenced exposure to multiple viewpoints as "advantageous" in terms of developing creativity:

> *It was interesting to see how my design ideas and other people's design ideas didn't always match up. … I sort of had this perception that there were ways to do things that were obvious because that's how working with robots I would think of things. And it wasn't to everyone, and it made me realize that I have a unique perspective, and that can be advantageous. But to get the optimal result with other people I should probably work with a team.*

She also later associates "the fact that it wasn't just [Mechanical Engineering] students" as part of the culture of the course that helped develop her creativity. For both Frank and Jessica, the fact that there were opportunities in class to both discuss their own designs and also see their teammate's work was part of cultivating their own creativity. Melissa, from the third team, references this as well: "It's interesting because the idea that I thought would be the best was not the one that was accepted…It's not just what I think, it's what everybody thinks." In this respect, Frank, Jessica and Melissa's experiences mirror Csikszentmihalyi's (1988) view that the interactions between a person and the society of members of the domain shape the creativity of that person. The idea of "mutual engagement" (Wenger 1998), where the community does things together, and the "relationships" and "social complexity" that exist amongst community members is central to learning in a "community of practice" and "situated learning" (Lave and Wenger 1991). The students remarking on group interaction spontaneously throughout my conversations with them illustrates that their interactions with their classmates stand out in their learning of creativity in *Solving Real Problems*.

Involvement of Professors

Throughout the interviews, students discussed the level of involvement of the professors. Two students referred specifically to the informal relationship between the professors and the students when asked about their creative development:

> *I probably feel that of all the professors I've had I feel more comfortable around Frey and Wallace and I mean there are a few others that come to mind. I mean the kind of informal nature, it made it really easy to get your ideas out there because it was very clear from the beginning that people weren't going to think you were stupid if you came up with something weird.*
>
> \- Allison

> *It wasn't like [the teaching staff] were sitting on a high podium saying "Ok class, now go be creative." You guys grabbed a pen and paper and drew with us. And I really liked that. In the back of my mind I remembered that [Professor Wallace] is a professor. But for the most part it was cool, cause he was playing with us, and that's awesome. So it really wasn't like a classical student professor relationship. It was more like he was someone who had more experience and could teach me but there's no ego, or separation involved which I think is really really important because a lot of kids are scared of professors, to tell them when they don't understand. You feel like you're on the same playing field as them almost.*
>
> \- Valerie

For Valerie and Allison, the "comfort" and the feeling of being on "same playing field" were important to them for expressing and developing creativity within the class. This illustrates Lave and Wenger's theory of situated learning; Valerie and Allison described the nature of the relationships and comfort level with others in the community when asked about the development of their creative skills.

Even if students did not mention the informal nature of the relationship with the professors, many referenced types of activities done with the professors. For Josh, a key moment was when Professor Frey "came up with having us eat the concrete and the process of digesting it would mix it." To Josh, "that was pretty out there, but it got us thinking out of the box, trying to come up with weird ideas." This experience also stood out in Tom's mind. Tom states "It was like my group and [Professor Frey] and we were just drawing random things … and we started just throwing out these random absolutely crazy ideas… That was really good for our creativity when we were just picking out random things out of nowhere." With first-year students working in teams for the first time in university, group work can be intimidating. Students spoke of fear of ideas getting "rejected" and "group conflict." For Josh and Tom, Professor Frey's willingness to model creative thinking helped draw out "crazy" or "weird" ideas from their own minds. This experience supports Jackson and Sinclair's work (2006) in higher education, where professors model the behavior they hope to cultivate in the students. Jackson and Sinclair suggest in order to develop creativity in students it is important "for a teacher to reveal their own creativity and show students what it means to them in their own practice." This notion of the professor as a mentor and model fits in to another key element of Wenger's "community of practice:" more experienced individuals act as mentors and teach newcomers through apprenticeship. Wenger connects this type of relationship with student learning, and the student reflections here do as well.

Confidence and Hands-on practice

When asked about *Solving Real Problems'* influence on their creative skills, two students, interestingly both females, mention the class's effect on their confidence in their own ideas and idea generation skills.

> *Where it helped me with creativity was in the ability to say I can, so it's just not as scary anymore. I was improving upon stuff, and I think that my improving upon design skills definitely improved more with [Solving Real Problems] than with anything else.*
>
> – Allison

Melissa echoes this statement by saying "I think I knew I was creative but I didn't have confidence in any of my ideas." Melissa and Allison linking of confidence to creative ability evoke Choi's (Choi 2004) research relating confidence in one's ideas and creative ability with creativity itself. A few of the students were unsure "how much creativity itself could be changed that quickly over time." Views such as this could imply that teaching creativity is not important. However, Melissa and Allison's statements indicate that increasing students' confidence in their creative abilities may be valuable to those individuals beyond a class.

Curiously, many of the male students also referenced tasks that would require building and machining skills when asked about creativity. Tom spoke of viewing creativity in his peers through watching a dorm-mate take apart and fix a speaker and then referred to his experience trying to keep two parts of his team's machine together since the fastener kept shearing apart as an example of his team's creativity. At multiple points, Adam and Frank talked about the East side of campus as being "creative" and demonstrating that by "building really crazy stuff." Josh's story of viewing creativity in his peers was about a teammate on the racecar design team who fixed a broken bolt in an unconventional way. He interprets this as "I think a lot of creativity comes from experience and trying different things, working your way through different situations." For these students, the fact that many of them feel like they got to "know the tools in the shop better" and "how to design things better" may be why one student indicated that they "definitely feel more prepared to work out in the engineering world and even just to fulfill [their] own creative hobbies." The acquisition of domain specific skills as necessities for creativity aligns with Gardner's (1993) study of creative individuals' lives in which he is concerned with individual ways of "mastering" their domains.

Reflections on the Lessons from *Solving Real Problems*

The experiences of these ten students in the inadvertent community of practice within *Solving Real Problems* appear to have had a positive influence on these students' perceptions of their creative thinking skills. It is possible that environmental factors linked with creative development such as consensual assessment, interaction between field, domain and individual, mentoring teacher-student relationships and the acquisition of domain-specific skills (Csikszentmihalyi 1988; Gardner 1993; Balchin 2006; Jackson and Sinclair 2006) are pronounced in "communities of practice."

Furthermore, although there was a lecture on creativity at the beginning of the semester and hands-on practice of brainstorming in the class and lab sections, the part of the class that stuck in the student's mind about creativity were the features related to course culture: the ability of students to exchange ideas freely during learning activities, the level and familiarity of interaction with the professors, and the use of hands-on activities to build student confidence in their ability to transform their ideas into reality. For team-centered classes, the ability to create a supportive classroom dynamic that fosters idea exchange between students and a culture of open-mindedness seems to be particularly useful in helping students develop their creative potential. This could potentially still be useful for classes that are not team-oriented as well: students also mention the value of hearing what *other* teams were working on over the course of the semester to their own creative development. This suggests that even if a student is working independently from other students, the culture of exchange of ideas is still beneficial. As noted by the student testimonials, a specific way of achieving this culture is for professors to model and mentor students in keeping open minds to the flow ideas during idea generation.

Another consideration given the content of this chapter is the value of maintaining an open dialogue between students and professors about their experiences in the classroom. Much of course evaluation is performed through paper surveys at the end of the semester. By maintaining relationships with students where they feel comfortable sharing their assessments of their own learning, particularly in creative development, it can open up new opportunities to encourage students to pursue their interests in a way that converges with class activities. It may seem that this type of recommendation is already expected in teaching; but the student reflections discussed in this section show that these kinds of relationships are more of an exception than the rule.

Ultimately, what the students of *Solving Real Problems* show us about creative thinking in an engineering design course is that what they remember as being important to their creative development was not lectures, but rather relationships and experiences with their professors in combination with hands-on activities where they could practice their skills. This speaks to the importance of diverging from traditional lecture formats when attempting to engage students' creativity. While many design courses in engineering are taught in similar fashion as *Solving Real Problems*, these lessons can extend beyond simply design classes to classes that are simply teaching students how to solve problems. Within the context of this thesis, this chapter illustrates some of the student reflections on what influenced their creative thought in an academic setting.

IV. Time and Team Influences on Creativity in *Product Engineering Processes*

Discovery consists of looking at the same thing as everyone else and thinking something different.

Albert Szent-Gyorgyi, Nobel Prize Winner and Physician.
Used in Product Engineering Processes lecture slides

Product Engineering Processes is the senior design capstone-style course in the Mechanical Engineering Department at MIT. This class requires students to work in teams ranging from twelve to eighteen students through a semester-long design process under a class-wide theme. The end result are alpha-level prototypes that address relevant market or community needs. The class focuses equally on learning how to design a product and on learning how to identify potentially compelling products. In other words, the design projects are not given to the students; instead students are asked to perform observations, interact with potential customers and brainstorm as individuals and as a group in order to recognize latent needs in the market and potential projects for further development. In my observations as a teaching assistant on this class, this process of problem definition can be one of the more difficult aspects of the course for students to appreciate. Often students wish to get to the heart of designing a product earlier in the semester, and have the problems defined for them. The teaching staff of this class believe that problem definition is one of the harder things to teach in an academic setting, and as Kristin Wolfe's senior Mechanical Engineering thesis shows this is an area that MIT's alumni are expected to excel in but believed that they did not learn well as undergraduates at MIT (Wolfe 2004).

The team structure for the class is an integral part of the student experience within the class. Students are first assigned to teams of twelve to eighteen students. These teams are determined by the course instructor based on student availability for lab meeting times: students preference-rank between five prescheduled three-hour weekly blocks of time, and then the professor of the class creates teams based on this. Usually students are given one of their top-two choices. These teams are further segmented into two sections determined arbitrarily by the course staff. Students work in these sections of seven to nine students on the first three deliverables of the class, then the sections merge into teams for the last three deliverables. Each section of students has elected officers: a systems integrator who manages meetings and coordinates project development and integration; a safety officer who watches out for safety in the shop and also safety issues in the use of the product; an information officer who attends to meeting minutes and interfaces with the course librarian; a tool officer who is responsible for the tool inventory in the shop; and a financial officer who oversees the team budget.

This course structure, like *Solving Real Problems*, is also heavily tied to the "Community of Practice" theory. There are several layers of experience built into each team of students: graduate student mentors, industry mentors, shop instructors, faculty and industry lab instructors and the course instructor. The entire community is learning at the same time as the students since the students define the problems they wish to solve. Oftentimes the teaching staff is there to advise students and help them move in the right direction, even if they do not know the best or "right" answers to the design problems the students face. As a result, the entire community is engaged in the mutual practice of researching and learning the engineering principles behind the designed products and interacting with the intended users of the products to learn how to best create them to suit the user needs. As a first-time lab instructor in Fall 2008, I engaged the many layers of experience in the class, both mentoring and working with the students directly but also seeking the advice and working with more experienced lab instructors to learn how to be a better lab instructor myself. This spirit of collaboration and taking advantage of the many resources the offered to the students permeates throughout the pedagogy of the course. Students' design reviews often consist of presentations in front of their peers and the community. The feedback that they receive in subsequent reviews is intentionally from different lab instructors and communications instructors so that students can get multiple viewpoints on their work. This also opens student's eyes to the idea that there is more than one correct answer to the problems they wish to solve; and that no matter what solution path they choose there will always be a person who agrees and another who thinks that the alternative would have been better. Helping students get comfortable with the idea of multiple acceptable solutions early in the semester is one of the big challenges of the course, and important for helping students feel comfortable solving problems creatively in the class.

Progress on the projects is delineated by a series of milestones over the course of the semester, each falling two weeks apart from one another on average. After all milestones, students receive verbal and written feedback from multiple lab instructors advising them as to areas they might want to consider more carefully and providing resources for moving the projects forward. Often, they will receive feedback from their peers and contacts as well; there is an online review form posted within 24 hours of each review showing the physical deliverable, as well as video recordings of the presentations and any materials (slides, posters, handouts) that the students have prepared in conjunction with the milestone. On the following page there is a diagrammatic representation of the project development process in Figure IV-1: Course Structure of Product Engineering Processes.

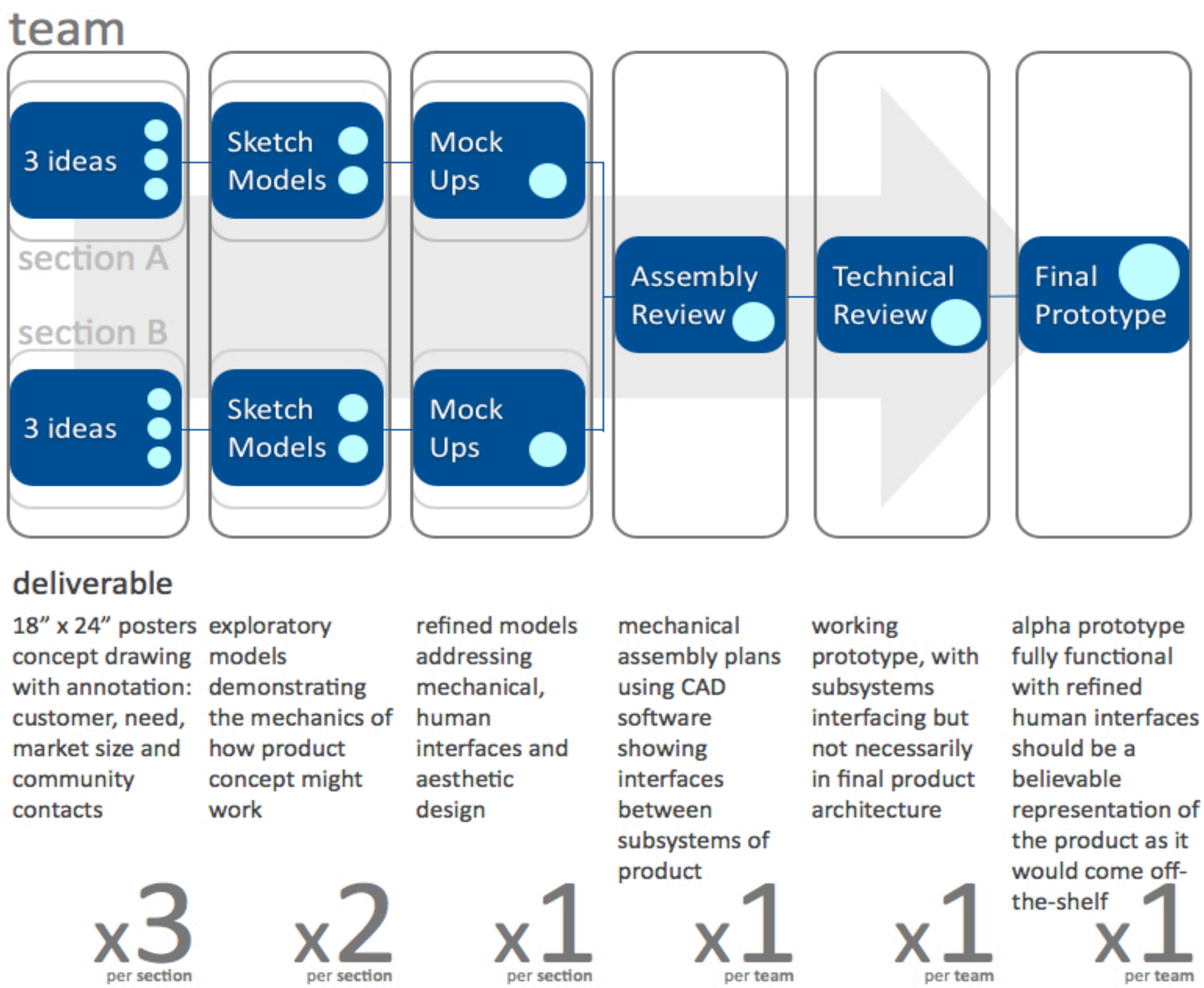


Figure IV-1: Course Structure of Product Engineering Processes

Lectures meet three times a week for one hour, and students meet for three hours once a week for their laboratory sections. The teaching team for this class is large: students interact with the main course instructor, three graduate student teaching assistants, two laboratory section instructors assigned to each team, a communications instructor assigned to each team, five machine shop instructors and a course librarian over the duration of the semester. Adding to these resources is a large group of mentors who volunteer their time and expertise to assist teams with the development process. However, it is important to note that the roles of the teaching staff are well-defined on the course website and therefore students know who to talk to when they need specific advice or help during the semester. Students know that each lecture will be delivered by the course instructor; that they will meet with their two dedicated lab instructors during their lab section; the shop instructors can help with sourcing materials and machining advice; communications instructors provide advice on presentations or team dynamics; and all the specific roles as delineated in Table IV-1: Roles of Teaching Staff in *Product Engineering Processes*. These defined roles and expected interactions over the course of the semester shape the rhythm of the class. In fact, when this rhythm is interrupted, for example, by lab instructors requiring a substitute for a section meeting, the student reviews show that they believe it negatively impacts the team.

Table IV-1: Roles of Teaching Staff in *Product Engineering Processes* *(Wallace 2008)*

Course Instructor	The course instructor sets the vision for the course, how the course is structured, and what is expected of all the participants. The lectures, project area, grading structure, guidelines, and milestones for the project are determined and administered by the course instructor. The course instructor is available to offer advice to or receive input from any student on all aspects of the course. The course instructor is also available to all teams for design consultation in the Pappalardo lab.
Teaching Assistants	The course TAs assist the course instructor in preparing materials for class and provide materials and resources for the teams. They work with financial officers to process team credit card purchases and receipts for reimbursement. They are available to all students to provide advice.
Lab Instructors	Each team has two faculty members (one per section) serving as their laboratory instructor. Lab instructors attend lectures and all of their team's labs. During lab students make most decisions and build prototypes, but the instructor facilitates team organization, the development of their product specification/contract, helps with risk assessment, concept selection, provides technical advice, assists with prototyping techniques, and conducts design reviews. One of the key roles of the lab instructor is to help teams maintain and adhere to their product development schedule.
Shop Instructors	The lab staff are employees of the Mechanical Engineering Department and work in the Pappalardo lab. They are available to help with advise on prototype fabrication, suggest ways to make parts easier to fabricate, and assist teams in the use of heavy or specialized machine equipment. The shop staff are valuable team resources.
Communications Instructors	Communications instructors are available from the Writing and Communication Center to provide feedback on your oral presentations and team communications in 2.009. They will participate in team meetings prior to major course milestones. They can provide feedback on past presentations by reviewing video with you and provide feedback during practice sessions.
Course Librarian	The course librarian provides tips on how to find information. They prepare resources specifically for the course, assist in class exercises to improve information gather skills, and work with team information officers by suggesting possible sources or search methods for different types of information.

Given that the students may be working on projects that require expertise in a variety of engineering domains, lectures are designed to give students a jumping off point from which to learn more about these specific areas. The repeating themes in lectures could be classified as broader problem-solving skills such as ideation, estimation, prototyping and testing; and group-work skills such as running meetings, consensus-building, team dynamics, and communications, see . While lectures cover the basics in a broad number of engineering areas, students gain depth in domain specific skills in areas such as electronics, machine design, human factors through working closely with their laboratory instructors, performing research on their own, and consulting outside experts in the domain - often other professors at MIT.

Table IV-2: Lecture and Lab Topics for *Product Engineering Processes* 2008

Week	Lecture	Lecture Topics	Lab Topics
1	Lecture 1	2.009 Introduction, Failed prototype test video	No lab this week
1	Lecture 2	Creativity and project introduction Brainstorming tutorial	
2	Lecture 1	Idea fair logistics, Teams and meetings	Electing officers and ideation
2	Lecture 2	Finding information	
2	Lecture 3	Observation and customer needs, Patents.	
3	Lecture 1	Estimation and testing	Exploring ideas and selecting for the 3 ideas presentation
3	Lecture 2	3-ideas logistics and more estimation	
3	Lecture 3	3-ideas welcome slide	
4	Lecture 1	Student holiday	More exploring and developing the team's idea area into concepts
4	Lecture 2	Sketch models	
4	Lecture 3	Teardowns and benchmarking Plastics identification Costing guidelines	
5	Lecture 1	Tips for successful projects, Sketch model presentation logistics, walking on water	Preparing for the sketch model review
5	Lecture 2	No formal class due to evening presentation - Time to work in lab	
5	Lecture 3	Sketch model feedback and water walk	
6	Lecture 1	Mockups, customer needs, and human use	Identifying and resolving key risks
6	Lecture 2	Scheduling and time estimation Origami ball time estimation experiment	
6	Lecture 3	Project consulting	
7	Lecture 1	Columbus day holiday	Preparing for the mockup review
7	Lecture 2	No formal class. Evening mockup review is this week. evening - Project consulting	
7	Lecture 3	Mockup feedback and specifications	
8	Lecture 1	Alpha prototypes, critique, and ethics	Making the decision
8	Lecture 2	Product architecture	
8	Lecture 3	Project consulting	
9	Lecture 1	Product form	Clarifying the system vision
9	Lecture 2	Safety and design for assembly	
9	Lecture 3	Chicken chart! and Project consulting	
10	Lecture 1	Assembly review	Resolving design details
10	Lecture 2	Assembly review	
10	Lecture 3	Technical review and debugging process Gorilla in the classroom demonstrates	

		inattentional blindness	
11	Lecture 1	Veteran's day holiday	Building the prototype
11	Lecture 2	2.009 business case , Product costing /economics model	
11	Lecture 3	Work session in Pappalardo lab	
12	Lecture 1	Patent literacy 101	Redesigning and improving the prototype
12	Lecture 2	Final presentation overview	
12	Lecture 3	Project consulting and work session	
13	Lecture 1	No class due to technical review	Planning rebuild and presentation
13	Lecture 2	No class due to technical review	
13	Lecture 3	Thanksgiving holiday	
14	Lecture 1	Presentation design	Prototype rebuilding, presentation designing
14	Lecture 2	Final presentation logistics, presenting data	
14	Lecture 3	Presentation practice sessions	
15	Lecture 1	No class due to evening presentations	Lab wrap ups
15	Lecture 2	Lab cleanup, course evaluation, and dinner	

Creativity Specific Course Activities

The overarching rhythm of *Product Engineering Processes* is a cycle of research, ideation, design, build, and test. This cycle repeats multiple times over the semester; commonly for the various project milestones and deliverables, and also when teams set internal deadlines for completing subsystems between the course deadlines. Throughout each stage of the class teams will often pull in outsiders to assist them in this process. This is supported by a course design that emphasizes the importance of gathering outside feedback from the onset. For the first course assignment, students must generate at least twenty ideas for new products within the class theme. After some minimal research, they select five of the twenty ideas, draw sketches and bring them into lab to present to their team section. After students present all of their ideas in this lab session, this is typically used as a starting point for a discussion followed by more idea generation in lab.

During the second week of the semester, an "ideas fair" is held that brings in organizations and individuals working on projects that relate to that year's course theme. These groups present specific needs that they have working in this field that they feel that the students could contribute to by designing a new product. Just after the ideas fair, there is an observation assignment that requires students to place themselves in a particular setting related to the course theme where they can watch users interacting with products and surroundings in order to determine latent needs. Teams are also required to maintain communication with a product contact who can represent a large subset of user needs for the products students are working on over the course of the semester. Each of these requirements are meant to provide inspiration for the ongoing ideation process that happens as students develop their projects over the course of the semester.

Many of the ideation specific activities come at the beginning of the semester to get students comfortable with the process and allow for instructor mentoring and feedback while students are still learning the mechanics of a brainstorming session. As the semester moves on, students often will do impromptu brainstorming sessions to solve specific problems with subsystems of their product, both with and without instructors present.

As stated earlier in this chapter, this class also reflects a "community of practice" teaching model in the many layers of experience levels in the course and in that the instructors are learning about new concepts along with the students. The large teaching staff who come from a variety of backgrounds (industry, academia, design firms) is used to give the students access to many different viewpoints, and often results in contradictory advice. We see this as a strength of the class, especially when trying to engage creative thinking in the students, because it allows students to see divergent thinking in practice and weigh many opinions in order to decide how to move forward on their projects.

Case Study Participants and Methods

The participants of this case study are the students who took *Product Engineering Processes* in Fall Semester 2007. This includes 122 students: 48 women and 74 men. All of these students were in their senior year of studies in Mechanical Engineering.

Data was collected through a variety of methods. The course required bi-weekly timesheets where students recorded any time spent on the class including who they were working with and what they were doing. An example of the data collected in the timesheets can be found in Table IV-3: Timesheet Information from Product Engineering Processes. These timesheets were completed using Acrobat Forms, a format which turned out to be time-consuming for both the students to use and the staff to process. Students downloaded a template at the beginning of the semester, kept it updated, and posted each form online every two weeks for collection by the course instructor.

Table IV-3: Timesheet Information from Product Engineering Processes

Date	Start Time: End Time:	Milestone: (pick one)	Activity Type: (pick one)	Working?	Description
		3 ideas presentation	class	alone?	
		sketch models	brainstorming	not alone?	
		mock up review	research	with team?	
		assembly review	design	with faculty?	
		technical review	prototyping	with client?	
		final review	testing/debugging	with other?	
		no milestone	presentation prep		
			meetings		
			other		

Students also filled out a team assessments to identify areas for improvement in group work for their teams. These were online surveys that most, but not all, students participated in. These were administered at two points during the semester. The questions contained in this review asked about specific aspects of the larger holistic picture of working well as a team. Each team was referred to by a specific color name: either red, green, yellow, blue, orange, purple or silver, which is how they will each be referred to throughout this section. Each of the aspects of the team review is delineated in the table on the following page, a full set of questions can be found in Appendix D.

Table IV-4: Aspects of Team Dynamics Addressed by *Product Engineering Processes* Team Review

Adapts goals	The team is able to think about what makes sense and adapts goals accordingly
Uses resources well	The team takes advantage of all resources available, and looks for opportunities to improve efficiency
Resolves conflicts	The team makes sure that conflicts are clearly resolved
Shares leadership	The team allows different people to control activities where they excel
Understands tasks	All team members know what is going on and what they should be doing
Provides feedback	Team members receive appropriate feedback on how they are doing
Makes decisions flexibly	The team realizes that different problems may require different approaches
Provides help when needed	Team members are willing help out by doing whatever needs to be done
Thinks creatively	The team is open-minded and willing to consider new ideas or change plans as needed
Is self-aware	Team members are aware of how their actions affect the team
Is committed	The team members are strongly committed to doing a good job
Is built on respect	Team members feel listened to and respected, and also listen to and respect others
Is well organized	The team efforts and meetings are efficient
Communicates professionally	Team communication is good, focused on the project, and not driven by personal agendas
Self-assessed effectiveness	Each team member considers her/his self to be effective in a team

Students also filled out online surveys at the beginning and end of the semester. These surveys asked students to compare their own competency in a variety of areas to the average senior in mechanical engineering; areas including product design, problem-solving, creative thinking, presentation of ideas and working in a team. Using the information about creative thinking ability, we can see the difference between how students self-assess before and after the class.

Lastly, I worked as a teaching assistant on the class both 2007 and 2008, and also as a lab instructor in 2008. This gave me an insider's perspective on course culture and student work habits. As someone who was close to the students' age and who also had been through the class, I was able to relate to the students in a way that allowed many of them to tell me their feelings about the class. From this combined set of data we can learn a great deal about how students experience creative thinking within the course.

Analysis of Student Data

General observations on time spent on brainstorming

The total amount of time spent brainstorming by each student varies widely. Some students record no hours brainstorming, while a small number rack up twenty eight to thirty five hours total brainstorming over the course of the semester, which averages out to two to three hours per week. The distribution of hours spent on brainstorming is shown in Figure IV-2 on page 45 below where the average reported number of brainstorming hours is eleven with a standard deviation of seven hours and twenty minutes.

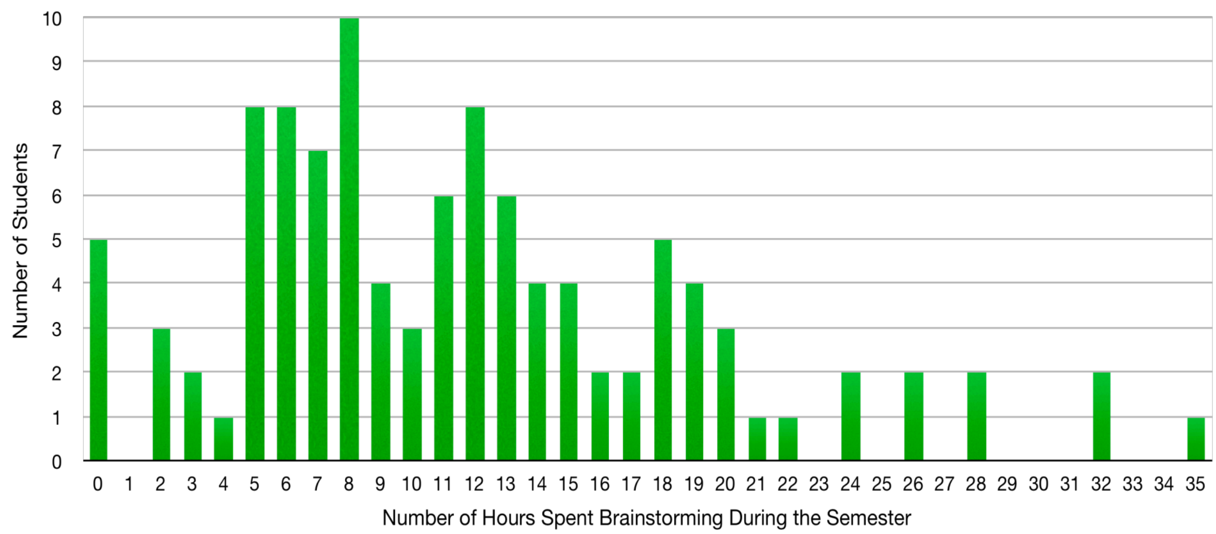


Figure IV-2: Hours Spent on Brainstorming by *Product Engineering Processes* Students

It is possible to visualized how this time was distributed over the semester, as compared to the total number of hours reported spent on the class by all of the students over the semester. As can be seen in Figure V-3 below, brainstorming peaks at the beginning of the semester, then declines steadily from there, even as students spend more and more time on the class.

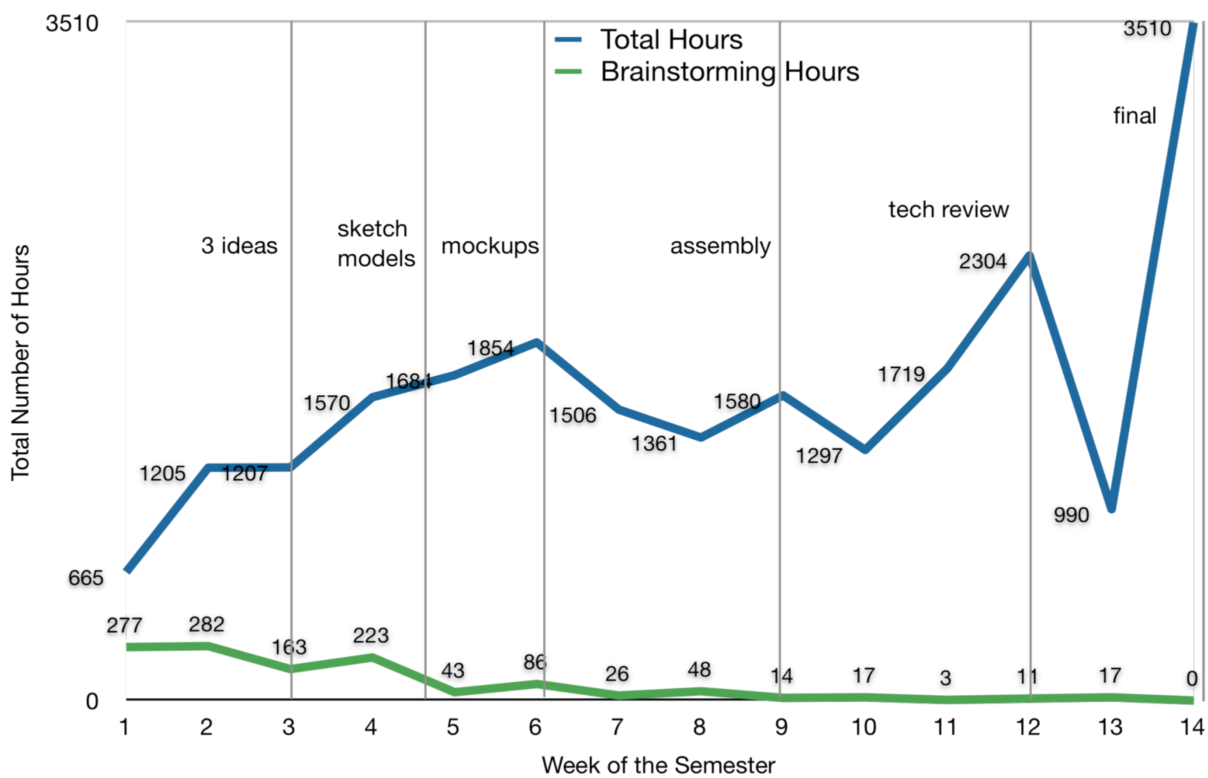


Figure IV-3: Hours Spent Brainstorming in *Product Engineering Processes* Over the Semester

It is interesting to note that midway between each review, brainstorming peaks, then as students get back to the mechanics of turning their ideas into physical implementations brainstorming declines again. This trend continues when brainstorming as a percentage of total time spent on the course is plotted:

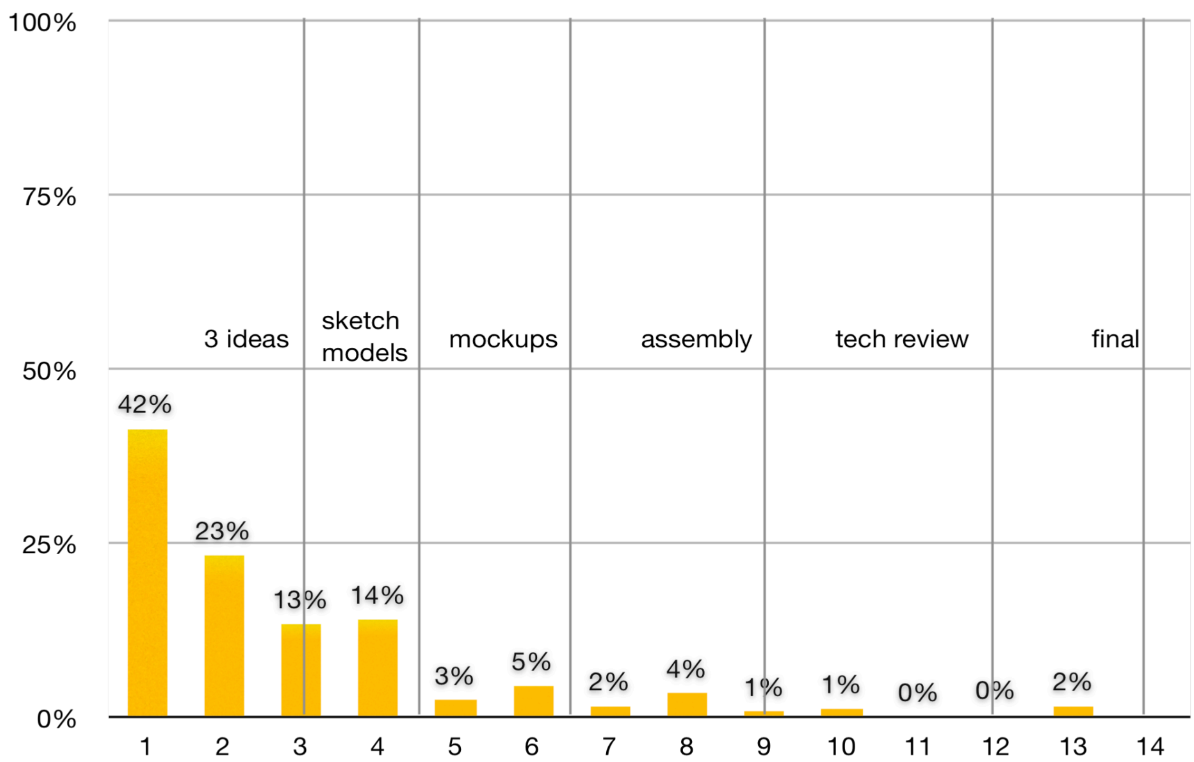


Figure IV-4: Brainstorming as a Percent of Total Time Spent on *Product Engineering Processes* Week by Week

Even with the total amount of time spent on *Product Engineering Processes* increasing in weeks between reviews, the relative amount of time spent brainstorming by the students during those periods is still higher than the down times right after a review is finished.

Brainstorming Companions and Team Data

Data was also collected about students' brainstorming partners: whether students report brainstorming alone or not, and who students are brainstorming with when they are not alone.

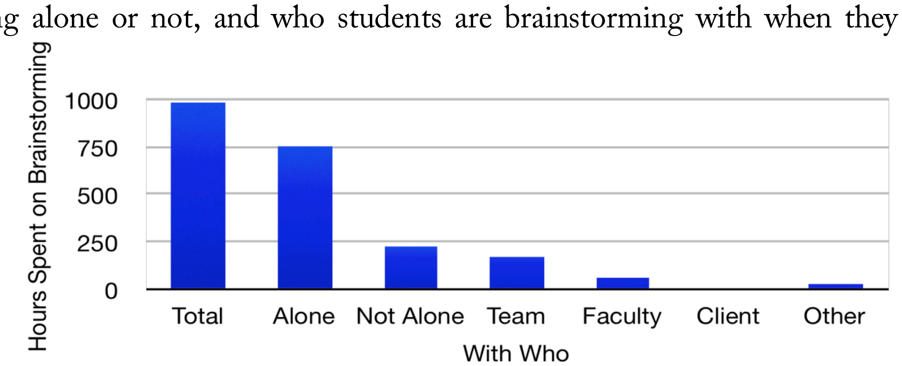


Figure IV-5: Student Reported Brainstorming Companions over the Semester in *Product Engineering Processes*

Students spent about 77 percent of their brainstorming time alone, with the 80 percent of the rest of the time with their team, and a smaller fraction with faculty. The relative amounts of time are shown in Figure IV-5 on the previous page.

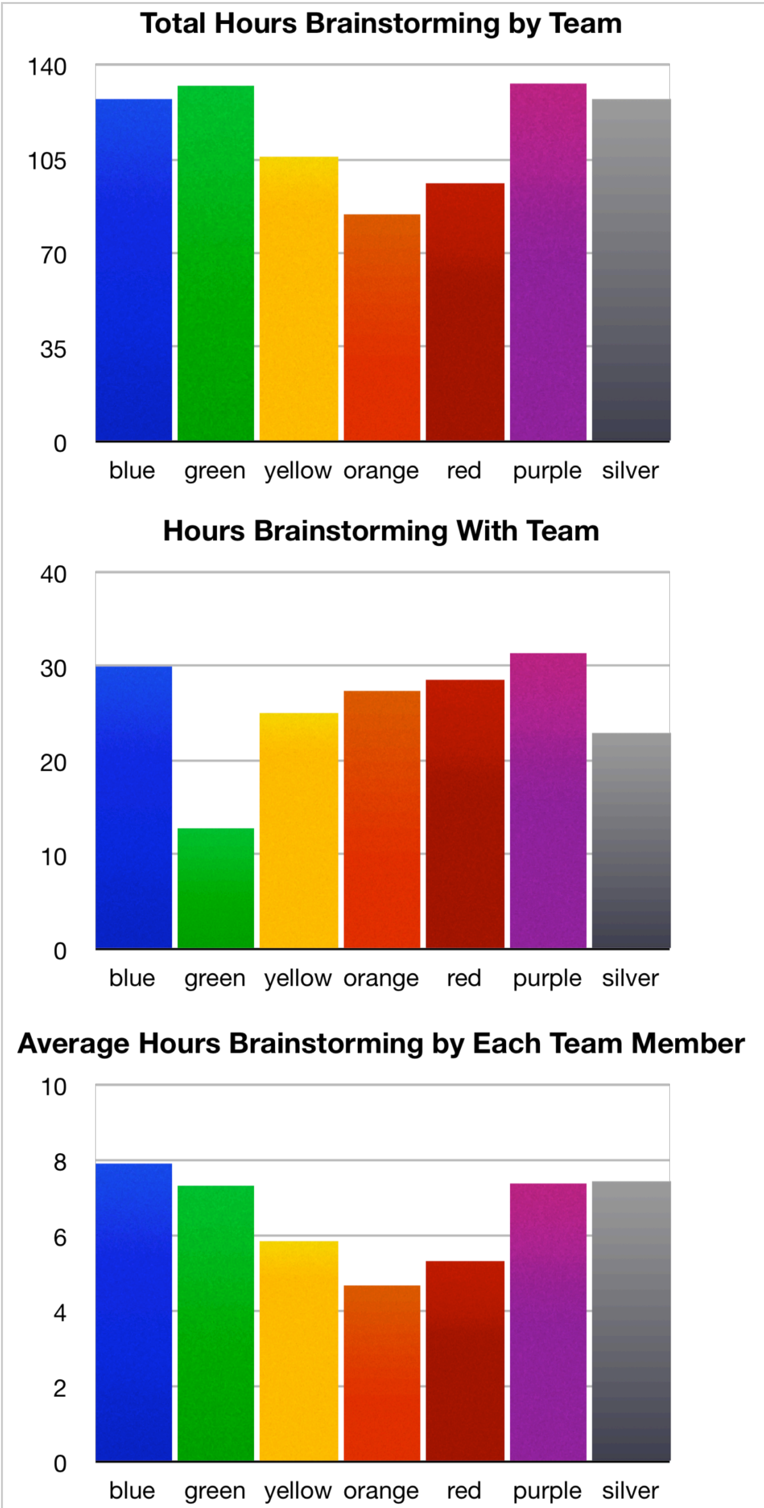


Figure IV-6: Trio of Graphs showing Brainstorming Time Allocation Across Teams in *Product Engineering Processes*

The variations between teams of time spent brainstorming and who that time is spent with is equally interesting. For instance, although Green team logs the highest number of hours spent brainstorming, they are the team that reports spending the least amount of time by far brainstorming with teammates. Similarly, team Orange reports the least number of total hours and the least average number of hours spent brainstorming, but they are one of the teams with a higher number of hours spent brainstorming together. When this is looked at in combination with the data on the team reviews of creativity (Figure IV-7), it appears that there may be a relationship between the total hours spent brainstorming by the team and average hours brainstorming by each team member with the team reviews of creativity: teams that spend more time brainstorming as a whole tend to have higher reviews of their team's creativity.

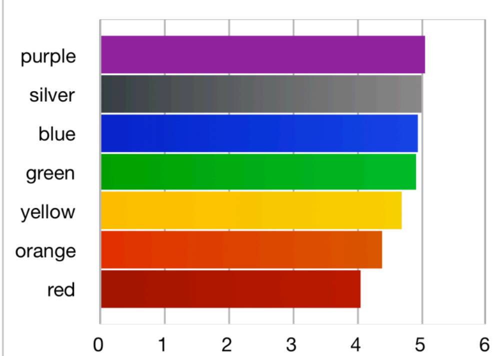


Figure IV-7: Reviews of Team Creativity by Team Members

Statistical Analysis

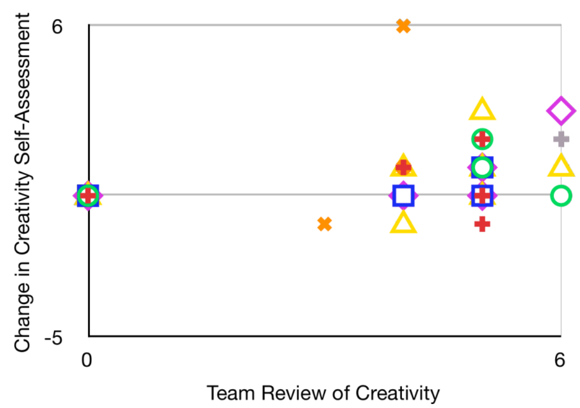
To investigate these relationships further, basic statistical calculations were run on the acquired data to see what could be learned about how time on task with brainstorming might influence student perceptions of both their own creativity and their teammates creativity. There are a few output variables that are of interest: student's self-assessed creativity at the end of the class, the difference between self-assessed creativity before and after the class, and the assessment of team creativity at the end of the semester. The input variables for which we have information are gender, ethnicity, team, amount of time spent brainstorming and with whom, as well as all of the team review factors. Each of these variables formulate a different subset of data points, the sizes of which are shown in Table IV-5 and are visualized in Figure IV-7 below.

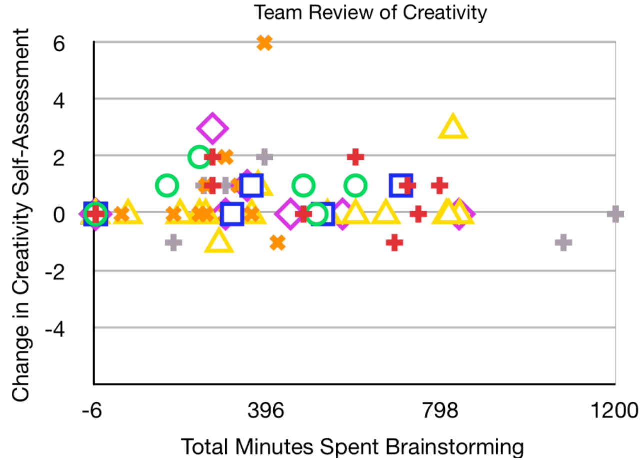
Table IV-5: Number of Data Points for Variables Collected for *Product Engineering Processes*

Team creativity	Pre-Class Creativity	Post-Class Creativity	Pre and Post Creativity
110	83	47	42

Figure IV-7: Visualizations of the Creativity Data from *Product Engineering Processes*

These plots show the distribution of data points with different variables plotted on the x and y axes. Each student is represented as a point in their team color. The only clear relationship seems to be between ΔCreativity and Team Creativity.
Top Left: ΔCreativity vs. Team Creativity
Bottom Left: Team Creativity vs. Individual Post-Creativity
Bottom Right: ΔCreativity vs. Minutes Brainstorming





As can be seen in the graphs there is potential for a linear relationship between the change in creative self-assessment and the reviews of team creativity, however each of the other graphs show little relationship between the x and y axes.

The correlations between all of the variables in the data collection process helped identify variables to investigate further in a regression analysis. Of particular interest are the variables that interact with post-class assessment of creativity, the change in pre-class assessment and post-class assessment of creativity, assessment of team creativity, and total minutes spent brainstorming. A summary of variables with interesting p-values and their correlation can be found in Table IV-6: Correlation Coefficients and P-Values for Variables of Interest in *Product Engineering Processes* below.

Table IV-6: Correlation Coefficients and P-Values for Variables of Interest in *Product Engineering Processes*

ΔCreativity Self-Assessment			Team Creativity		
Variable	p-value	R	Variable	p-value	R
My team members want to fulfill all task requirements before leaving.	0.01	-0.46	Team Dummy Variable	0.03	-0.37
My team members take ownership for each others' performance and will contribute whatever it takes.	0.04	-0.36	I take advantage of all the resources my team has at its disposal.	0.06	0.32
I understand our mission and the goals and standards our group is expected to meet.	0.04	0.36	My team members know that different situations require different decision-making styles.	0.08	0.31
			Female	0.09	-0.30

Total Minutes Brainstorming			Minutes Brainstorming With Team		
Variable	p-value	R	Variable	p-value	R
All team members know how to provide feedback to each other.	0.02	-0.40	I am committed to completing the tasks that my team or task force is currently accountable for.	0.07	-0.32
I am committed to completing the tasks that my team or task force is currently accountable for.	0.07	-0.31	I am unconcerned about status amongst my team members.	0.08	-0.31
My team or task force stays together until it finishes each task.	0.08	-0.31	I have knowledge about what each team member is doing when we are working on a project.	0.08	0.30
Team meetings are highly productive and are conducted in an efficient and a time-conscious manner.	0.09	-0.30	My team members know that different situations require different decision-making styles.	0.08	0.30

As can be seen in the above table, few of the seventy variables tested for correlations with the above variables are found to have statistical significance. Of those that are found to have low p-values, in this case less than 0.1, all are only found to have low correlation with each of the output variables – none are close to one or negative one. Interestingly, time spent on brainstorming did not factor significantly for any of the self or team assessments of creativity.

The examination of relationships purely in terms of signs rather than magnitudes shows us how two factors correlate with one another. Looking specifically at the change in individuals' creativity assessment from the beginning to the end of the class, we can see that the two factors related to team performance actually have a negative correlation with change in self-assessment of creative thinking skills. This means that higher agreement with the statements "My team members want to fulfill all task requirements before leaving" and "My team members take ownership for each others' performance and will contribute whatever it takes" actually correlate with lower self-perceived increases in creative thinking ability. Both of these statements in essence represent individual team members exchanging some of their own autonomy to the decision making and ownership of the team as a whole. Seeing this, it may make sense that each of these two factors correlate with lower perceived increases – and in some cases decreases – in creativity. This is in contrast to another question on the team review, "I understand our mission and the goals and standards our group is expected to meet." A higher level of agreement with this statement correlated with a larger increase in creativity self-assessment by the end of the semester. Perhaps a common sense of purpose and vision across a team help the individual members express and develop their creativity over the course of the semester. Or perhaps a common sense of purpose and vision make the students in a team feel more creative by the end of the semester.

Similarly, for the assessments of team creativity there are two aspects of the team review which had weak positive correlations: use of resources by the team member and different decision-making styles for different situations. It is possible to conjecture reasons why this may be the case: perhaps creative thinking teams apply their divergent thinking skills both to their project and to their decision making processes, resulting in a positive correlation between these two factors. As for full use of resources available to the students, on teams that rate themselves as more creative, perhaps they also view their use of resources creatively and engage those resources in ways beyond the average team. Two team and individual characteristics show as negatively correlated with team creativity – one the dummy variable for a specific team that struggled during the initial idea generation and concept incubation stage at the beginning of the semester, and the other which shows that females in the class on average rate their team's creativity slightly lower than males.

For correlations with total minutes spent by each class member brainstorming, there are only negative correlations with the variables. They still are only low correlation values, but regardless may be interesting to take a closer look at what the data says. The four team review variables that showed negative, statistically interesting, correlations with time spent brainstorming by each individual are: "All team members know how to provide feedback to each other;" "I am committed to completing the tasks that my team or task force is currently accountable for;" "My team or task force stays together until it finishes each task;" "Team meetings are highly productive and are conducted in an efficient and a time-conscious manner." For each of these statements, higher levels of agreement with the statements correlated with slightly lower values of time spent brainstorming. It is more difficult to speculate for the reasons for these correlations given that time spent brainstorming is more likely to be influenced by outside factors: including total time spent on this class, the course load of each individual student, other demands on student time and specific task forces that each student serves on within their team. For these reasons I limit the exploration of this area to the correlation analysis, and only include time spent brainstorming as an input into the regression analysis in the next section, rather than looking at it as an outcome.

Basic regressions were also run in MATLAB using the available data. The input variables were the same as the input variables for the correlation analysis, with the exception of the variables included from the team review. For the team review characteristics, only variables that showed statistically significant at the level of 90% confidence, where $p < 0.1$, were included in the model for the change in individual's creativity. Two separate models were set up, detailed in Figure IV-8 below.

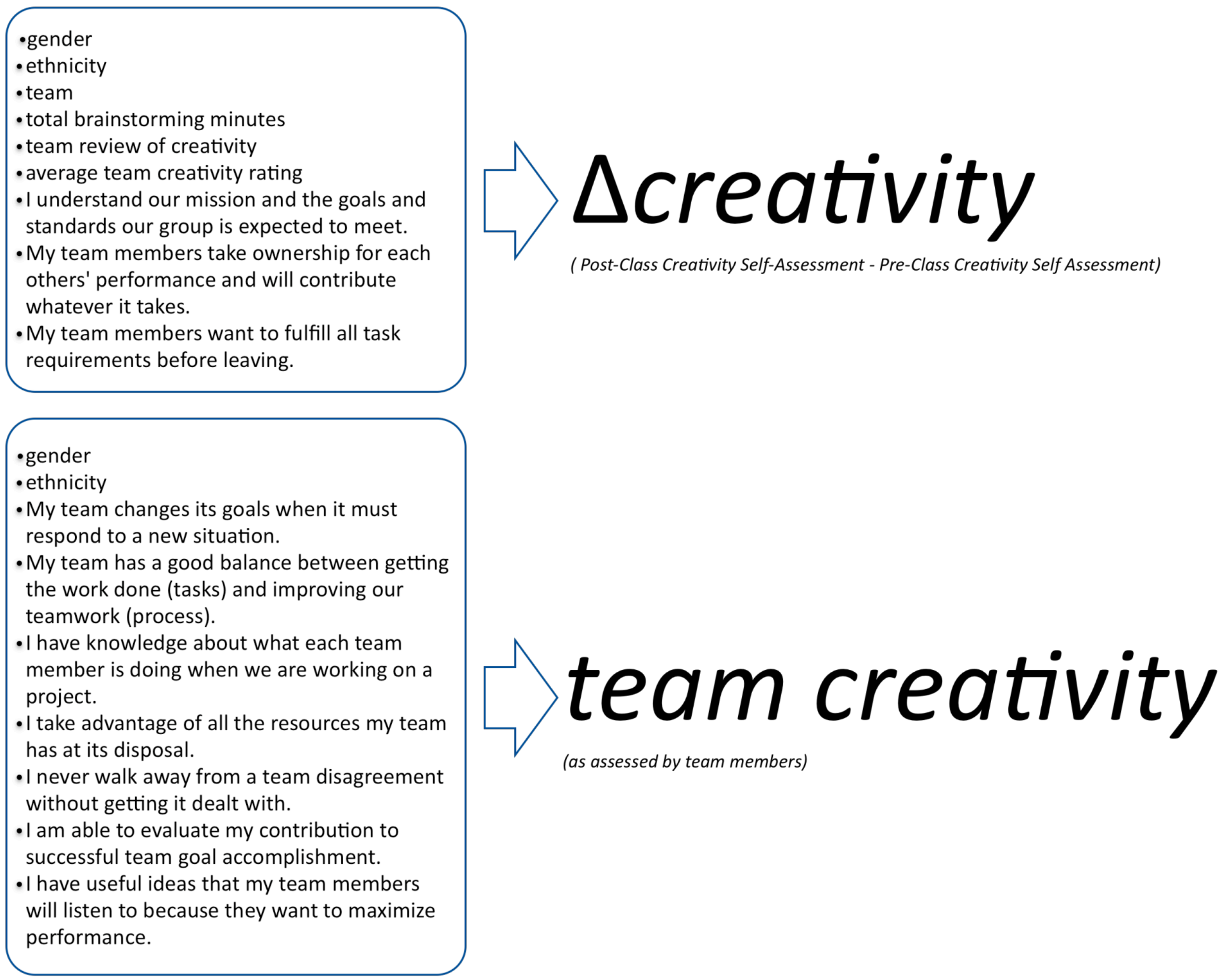


Figure IV-8: Regression Models Used to Analyze *Product Engineering Processes* Data

For the team creativity model, the team dummy variables were eliminated from the input variable set due to their correlations with the team review factors. This the model to construct correlations between how students perceive their teams to be and their perceptions of their teams' creativity rather than strictly separating the teams apart from one another in the analysis. Instead, a lower threshold was used to separate factors to include from the correlation analysis, and factors with insignificant coefficients were removed from the model. This is not an ideal method of model construction where typically the inputs would be based on a theoretical model and then data would be gathered in accordance with the model. Since the data used in this section is based on a dataset that had already been collected, the technique of mining the data for information and experimental model building is appropriate.

When these models were run in MATLAB to gain a better understanding of how these factors may correlate with one another there were some interesting results. For the change in the students' assessment of their creative thinking ability, the overall p-value for the model was 0.01 and the R-square statistic was 0.62, meaning that the model accounted for 62% of the variation in the dataset and that there is a 1% chance that the null hypothesis is true, or in other words, that the variables used as inputs in the regression model have no predictive value in actuality. The regression coefficients, with their 90% confidence intervals, are shown Figure IV-9 below.
With the team coefficients shown on the left-hand side of the graph, the values of the coefficients

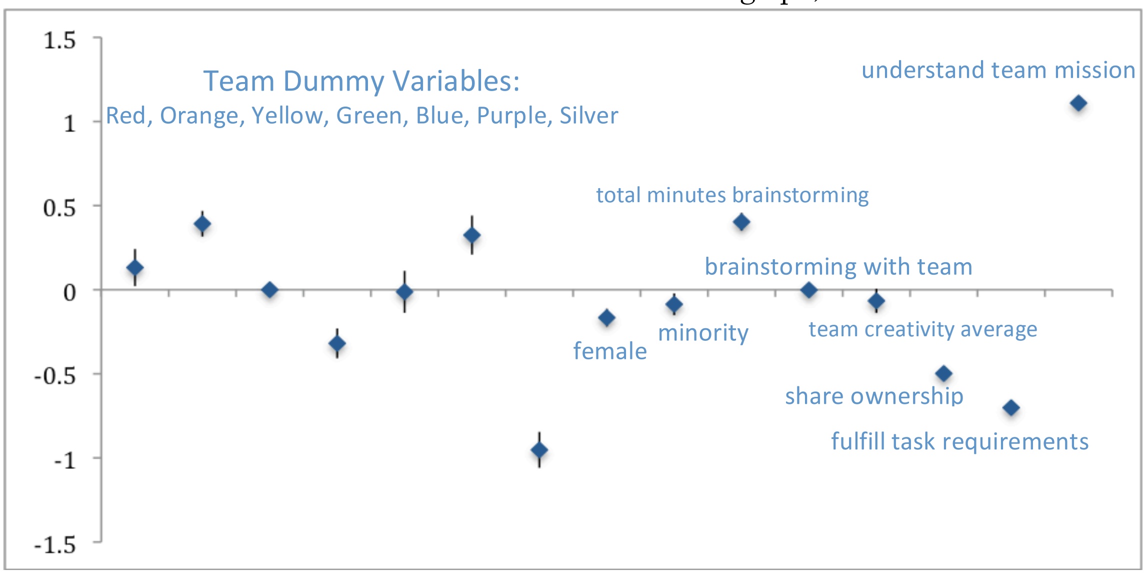


Figure IV-9: Regression Coefficients for Individual ΔCreativity Model

are less important than the differences between them. Not knowing specifically what makes each team differ from one another, or how to compare the teams to other teams working in design classes means that it would be hard to extrapolate meaning as to how team assignment might influence an individual's development of creative thinking skills. The important message in the data is that team assignment matters: students were randomly assigned to teams, with the exception of scheduling conflicts. That the regression coefficients are significantly different and the 90% confidence intervals for the most part do not overlap means that either there is likely to be a causational relationship between team dynamics and individual creativity development or that the factors that influence team dynamics are likely to influence creative development as well. We cannot say conclusively if either of these are the case, but clearly team assignment and individual's creative development are intertwined.

For the factors outside of the team dummy variables, a few of the coefficients are negligible: gender, ethnicity, brainstorming time with team, and the average rating of team creativity by the team members. Total minutes brainstorming did have a positive correlation with individual creative thinking development, as did agreement with the statement "I understand our mission and the goals and standards our group is expected to meet." Interestingly, agreement with that statement actually has the largest absolute value of regression coefficient compared to all other factors in the analysis.

The team creativity model proved to have a lesser R-square value (0.21) than the individual creativity model, meaning that the factors included only account for 21% of the variation in the data. However, the p-value at 0.01 shows that the model does have statistical significance; and that we can reject the null hypothesis that the included factors have no relationship to the team creativity ratings.

Unlike the change in individual creativity rating model, the regression coefficients for the team review factors in the team creativity model are small, all falling within the range of -0.25 to 0.25. They can be seen in Figure IV-10: Regression Coefficients in Team Creativity Model below.

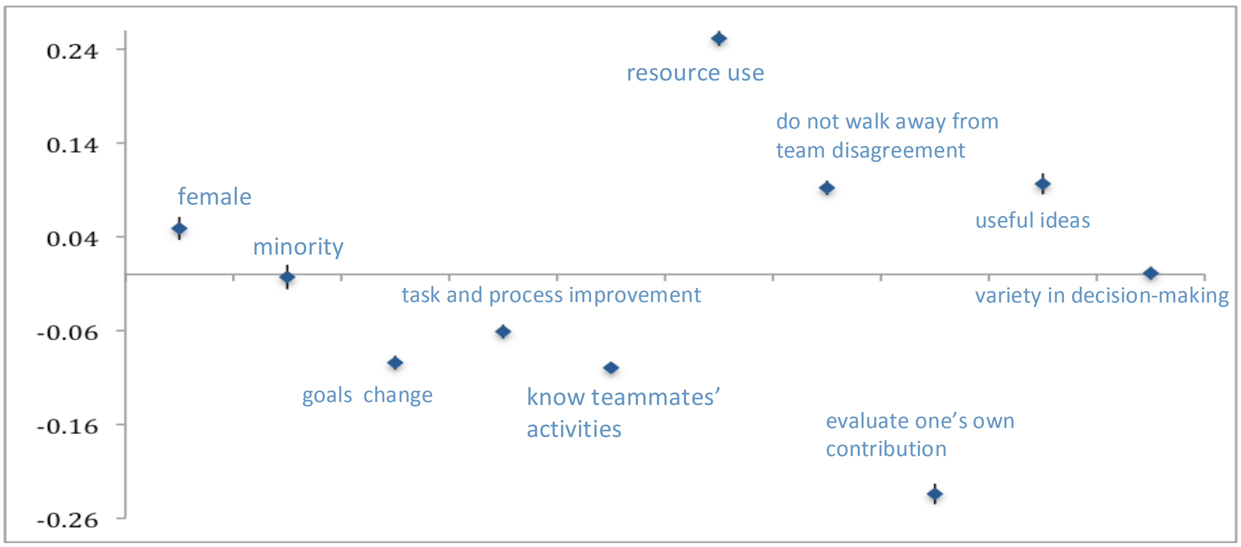


Figure IV-10: Regression Coefficients in Team Creativity Model

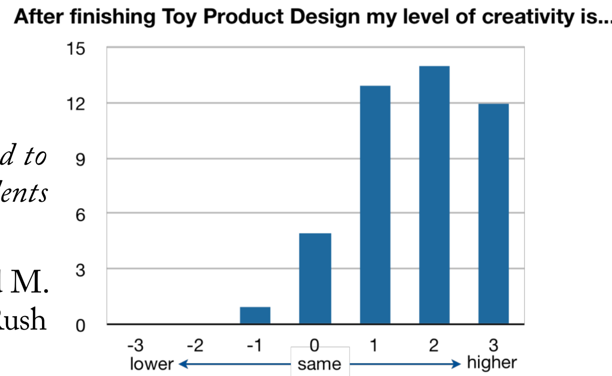
The two factors with the largest regression coefficients were levels of agreement with the statements "I take advantage of all the resources my team has at its disposal," and "I am able to evaluate my contribution to successful team goal accomplishment." Higher levels of agreement with the statement about using all resources available to the team correlated with marginally higher assessments of team creativity. On the other hand, higher levels of agreement with statement about the ability to identify one's own contribution to team accomplishments corresponded with marginally lower assessments of team creativity. In both cases, the regression coefficient is comparatively low when looking at these results next to the results of the individual creativity model. This is surprising, because it could be expected that the reviews of team characteristics would have stronger correlations with the reviews of team creativity than they would to have to each individual's perceived increase in creative thinking ability. However, this is shown to not be the case.

Summary

The themes of the data from *Product Engineering Processes* are two-fold. Correlations between time spent brainstorming and assessment of creativity, both an individual's and a team's, are negligible. This can either mean that amount of brainstorming does not affect creative development, or that it does not factor into an person's assessment of their creative development. It could also mean that students report brainstorming regardless of the quality of brainstorming, and therefore total minutes of brainstorming have no significant effect on creativity assessment, but minutes of quality brainstorming might. Regardless, simply including brainstorming as a course activity or class assignment is not likely to have a significant effect on student's creative self-efficacy.

The other information in the data collected from *Product Engineering Processes* students is that team assignment does influence student creative self-efficacy. Even though there was an absence of factors correlated with team creative assessment, the team factors proved quite influential on student's self-assessed creative development. While a causational effect cannot be proven given the research design, the relationship between team creative assessment and student creative development is clear: students that rated their team's creativity higher also tended to rate their own creative development higher. This is compelling for course designers, who could manipulate the characteristics of their teams accordingly or periodically have students assess team creativity in order to identify teams to assist with idea generation or brainstorming activities.

V. Designing Classes to Foster Creativity in Engineering: *Fundamentals of Engineering Design* and *Toy Product Design*



The results of a end-of-semester survey administered to Toy Product Design students show that most students report an increase in self-efficacy in creativity.

Survey administered by B. Kudrowitz and M. Rush

As can be seen in the literature, there are several philosophies and approaches to teaching creativity, especially within engineering education. In this section, two different first-year engineering design courses at MIT: *Fundamentals of Engineering Design* and *Toy Product Design* are profiled. In end-of-semester surveys, a majority of students in each of these classes indicated that they believed that their level of creativity had increased over the course of the semester. Each of these classes had creative thinking skills as one of the learning objectives for the students, but they had very different ways of approaching this learning objective through classroom activities and assignments. The goal is to layout these classes in such detail that the reader can understand what it is like to be a student in these classes or a teacher for these classes. I will also intersperse some of my personal reflections from observing each class in depth by serving as a teaching assistant.

Overview

Explore Sea, Space and Earth: Fundamentals of Engineering Design, taught by Professors Alex Techet, Alex Slocum, Dava Newman and Ed Crawley, is a first-year design course targeted towards freshmen. It is offered jointly underneath the Mechanical Engineering and Aeronautics and Astronautics Departments at MIT. Taught for the first time in Spring 2007, the lecturers and graduate teaching assistants used team-teaching approach where lectures were rotated through the four professors. Emphasis was placed on student's self-directed design, where students were given the specific challenge of gathering materials placed at the bottom of a pool and then could decide how to approach the design-and-build of a machine with the input of their professors and teaching assistants. Students worked in two to three person teams of their choosing. The design process was specified for the students to the extent of giving them a schedule of when they were expected to complete the most critical module of their design, as well as test their machine in an underwater tank. For the end-of-semester competition each team was expected to have a working underwater remote operated vehicle that could be used to gather the materials as specified at the beginning of the semester.

Toy Product Design is led by a Mechanical Engineering graduate student, Barry Kudrowitz, with guidance from Professor David Wallace. It began as a seminar in Spring 2006, and has steadily grown in enrollment with each successive offering. In Spring 2008, the implementation of which will be described in this section, it was an introductory offering under the Department of Mechanical Engineering. Lectures are all delivered by Barry Kudrowitz with the exception of occasional guest lecturers to go over prototype construction, story telling, and other specific topics. Students worked in small groups of on average five students per section, although this depends on the course enrollment from year to year. As with the *Explore* class, emphasis is placed on student's self-directed design, however the end goal was open-ended: only an overarching theme united the class projects. In Spring 2008 this theme was "toys that teach science and engineering." The student work culminates in "Playsentations" at the end of the semester, where students present their working prototypes to an audience of fellow students and guests from the local toy and product design industry.

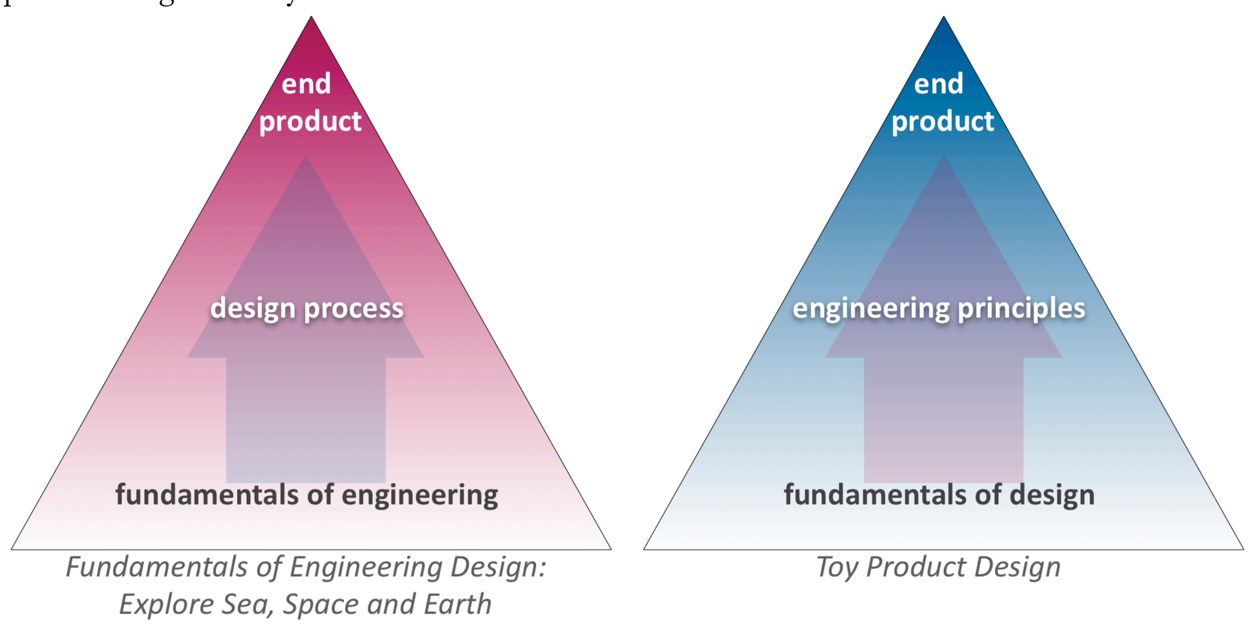


Figure V-1: Pedagogy of *Fundamentals of Engineering* and *Toy Product Design*

Fundamentals of Engineering and *Toy Product Design* were each based on two different models of teaching design to beginner students. *Fundamentals of Engineering* aimed to give students a broad understanding of each engineering concept that is the focus of higher level engineering courses.

Toy Product Design taught students the fundamentals of the design process, and relied on students learning the engineering fundamentals relevant to their design project through this process. These two philosophies are depicted in the diagram above (Figure V-1).

Explore Sea, Space and Earth: Fundamentals of Engineering Design

Explore Sea, Space and Earth: Fundamentals of Engineering Design was based on a bottom-up teaching, or "fundamentals-to-big picture," approach; meaning lectures were formatted to give a broad covering of the basics; focused on general engineering concepts that were not specific to their design project. This course was aimed at freshmen still undecided in their choice of major as of spring semester. Lectures were meant to serve as a taste or introduction to a topic that students would spend a semester learning about as upperclassmen in engineering classes. As such, topics were presented in a manner that could be applicable to any of the engineering disciplines in order to help students decide between these three majors; Mechanical Engineering, Ocean Engineering and Aerospace and Astronautical Engineering applications were those highlighted most frequently in class since these were the disciplines of the professors. The course was offered under two departments: the Mechanical Engineering Department and The Aeronautics and Astronautics Department, since Ocean Engineering is now a specific track underneath the Mechanical Engineering Department.

The teaching team outlined learning objectives during course development in fall 2006, the semester prior to the first offering of the class. These learning objectives were:

- Actively participate in reading and discussing the Exploration and Engineering Fundamentals materials
- Introduce, use, and calculate engineering fundamental principles
- Propose and evaluate engineering designs for human-operated robotic designs and understand societal implications.
- Effectively communicate, research and document engineering analysis and the design process for an operational system.
- Frame and resolve ill-defined problems, and design and operate a robotic vehicle for exploration.
- Participate as a contributing member of an engineering team comprised of four-six students.

Design Project

The central focus of this class outside of lectures was the semester long design-and-build project. This project was chosen by the teaching team to best suit freshmen and to have elements that were applicable to exploring sea, space and earth. Students worked in teams of three to four in order to design and build underwater remote operated vehicles (ROVs). Students in the *Explore* class chose their own teams for their design and build projects. These teams in turn worked closely with graduate student teaching assistants during their lab sections to develop the mechanical elements of their underwater vehicles. At the end of the semester, the ROVs participated in a challenge to gather materials at a depth of fifteen feet. This event is viewed more as a celebration of the student's accomplishments than as an opportunity to pit teams against each other. A pizza party was held for the students and later each team has a chance to view underwater video of their remote-operated vehicle in action. The 2007 contest setup can be seen in Figure V-2, where the object depicted is submerged at the bottom of a sixteen foot pool. This setup changes from year to year to allow for the instructors to incorporate alternative challenges and let students explore a new solution space.

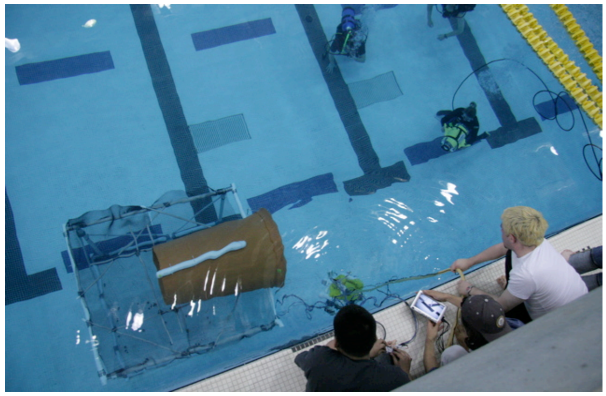


Figure V-2: Underwater Location of Materials for Retrieval for ROVs

Construction materials for the ROVs were limited to PVC pipe, zip ties, contact cement and six motors. Teams were limited to six motors for motion of the ROV as well as the mechanisms of the materials-collection device on the machine. One of these motors had to be prepared by water-sealing, but left aside as a replacement motor in case any of the motors should fail. For navigation, students were provided with an underwater camera that would be hooked up to a surface monitor. Students were also given directions for how to construct a light-emitting diode (LED) bank to provide light for the underwater cameras.

The course staff put heavy emphasis on successful completion of a working prototype; the general belief was that if the students failed to create a machine that works, then the teaching staff had also failed at their job. In 2007, four of the five machines were able to successfully collect materials and navigate the pool. The fifth machine had trouble with water-sealing the motors, and as a result had difficulty controlling movement underwater.

Lectures and Labs

The lectures for the *Explore* class focused on breadth over depth of exposure to several engineering concepts; the topics are detailed on the next page in Table V-1: Syllabus for *Explore Sea, Space and Earth*. At the end of the semester, lecture times were left unscheduled in order to give students more time in lab to build their projects. End-of-semester lectures were also planned to give students wider exposure to engineering; guest lecturers spoke about their research and experience in ocean and space exploration, as well as the ethical and societal implications of engineering decisions. Two 1.5 hour lectures were held each week, as well as a three hour lab section. Students would take the general concepts learned in lecture and learn how specifically to apply them to their semester design and build project outside of class or during lab. In addition to the six hours of class time, students were expected to spend about three hours each week on homework.

Table V-1: Syllabus for *Explore Sea, Space and Earth*

Week	Lecture 1 Topic	Lecture 2 Topic	Lab Topic
1	Course Introduction	Intro to ME/OE & Aero/Astro, Sketching	Lab Safety, Writing & Communications
2	Equations of Motion	Momentum, Energy & Power	Solidworks & Website Building
3	No Lecture - Holiday	Structures I	Machining Exercises & Practice, Brainstorming
4	Lift, Drag & Propulsion I	Structures II	Machining Processes, Play with Materials in Kits
5	Linkages & Bearings	Lift, Drag & Propulsion II	Machining, Peer Review
6	Mechanical Elements - Gears	Mechatronic Elements: Motors	Peer Review on Solid Model of Concepts
7	Systems Engineering	Team Progress Reports	Continue Machining
8	No Lecture – Lab Time	No Lecture – Lab Time	Project Work Time, Design Notebook Review
9	No Lecture – Lab Time	Ethics, Societal Impact of Engineering	Project Work Time
10	No lecture – Holiday	Space Exploration Guest Lecture	Project Work Time
11	Ocean Exploration Guest Lecture	No Lecture – Lab Time	Project Work Time
12	No Lecture – Lab Time	No Lecture – Lab Time	Wet Test Week
13	Final Design Competition	No Lecture – Presentation Practice	Build, Test, Build
14	Final Team Presentations	End of Semester	No Lab

Week to week, labs were run by mechanical engineering graduate student teaching assistants and Professor Alex Techet. Labs were exclusively focused on projects work time and also were a weekly opportunity to receive feedback from peers and instructors on project design. Collaborative design was seen as an integral part of the class: both in that students worked as teams, but also because they were expected to critique and aid other teams during the lab times. In addition, software tutorials on website design, solid modeling and basic machine skills were provided during lab time in order to help students complete the semester's requirements.

In my observations, the experience of the students in *Fundamentals of Engineering* could be seen as somewhat discontinuous: in a given week, they could interact with as many as three different instructors out of a teaching team of seven. Accommodating four professors' schedules during lecture scheduling meant that at times specific topics, such as structures, were not addressed in consecutive lectures but instead separated by one or two other lecture topics. A large teaching team meant that students had to adjust lecture-to-lecture on the delivery of lectures rather than solely focusing on content, especially since often the professors did not attend one another's lectures, making it can be harder to draw ties between content. On the other hand, some of the benefits of having a large teaching staff meant that students were exposed to a large number of professors working in a variety of different specialties in both mechanical engineering and aeronautical/astronautical engineering. Having this exposure to a breadth of engineering specialties meant that students had someone that they could turn to if they were particularly interested in a topic.

Grading and Deliverables

This class was designed to fulfill a communications requirement for the students, meaning that along with the engineering skills, students should develop their presentation, written and interpersonal skills during the semester as well. Class participation, in-class presentations, a paper and the maintenance on an online design portfolio all contributed to the development of communications skills. The design paper was due midway through the semester and was on a topic of the student's choosing. The class made heavy use of new media: web-based technology was used to disseminate information in the *Explore* class. A course webpage hosted on MIT's standard course management system was used to post the syllabus, lecture materials and readings. In addition, each student was expected to prepare a web-based portfolio of their design process chronicling the design process by the end of the semester. As can be seen in Table V-2, the grades for the semester were half based on the design project and half on other deliverables over the course of the semester.

Table V-2: Grading Rubric for Explore Sea, Space and Earth

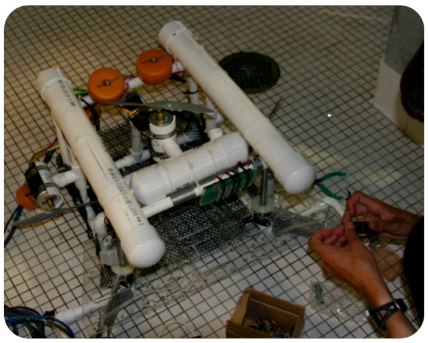
Peer Review	5%	Project – breakdown as follows:	
Participation	5%	Does it Work	15%
Weekly Design Notebook Review	15%	Design Review #1	10%
Research Paper	10%	Design Review #2	10%
Final Design Notebook	15%	Final Design Portfolio	15%
Total	50%	Total	50%

Creativity-Specific Aspects

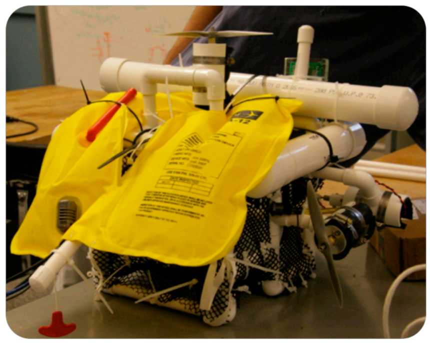
There were several aspects of *Explore Sea, Space and Earth* that could be seen as influencing students' creative processes. Taking into consideration the community of practice and systems view of creativity, we emphasized the acquisition of domain specific skills through hands-on work with people more experienced than the students, as well as creating many opportunities for the sharing and exchange of ideas in several aspects of the course. However, there were also limitations and constraints on students' creativity that the teaching team felt were necessary given that this was a first-year design and build course.

An explicit goal of the design project was to impart domain-specific machining skills that students could use in their design and build work in the future. Early on in the semester students were given a small machining exercise that they could work on in conjunction with the teaching assistants. Throughout the semester their work in the labs was hands-on, with teaching assistants helping them to decide how to allocate their time any given day. Students were given a lecture on sketching at the beginning of the semester so they could begin to feel comfortable taking the ideas from inside their head and placing them into a form where others can understand how they envision their designs. Both the machining exercise and the sketching lecture were meant to give students the tools to make physical representations (drawing or models) of their creative ideas.

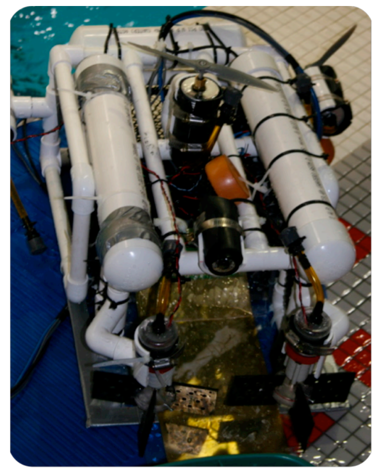
As for the design project itself, there was freedom of decision for the students in certain parts of their design and not in others. The design project was limited and specific in scope: designing an underwater remote operated vehicle. Students did not know in advance of registering for the class that this would be the specific nature of course. Students were given kits of construction materials and instructions on assembly, and this is reflected in the fact that most of the student machines had similar bodies and frames. However, students were given freedom to deciding how they would collect materials underwater and this resulted in five very different methods of collection. In this aspect of their designs they were able to express their creativity, shown in Figure V-2: Pictures of Student Designs from *Fundamentals of Engineering: Explore Sea, Space and Earth*.



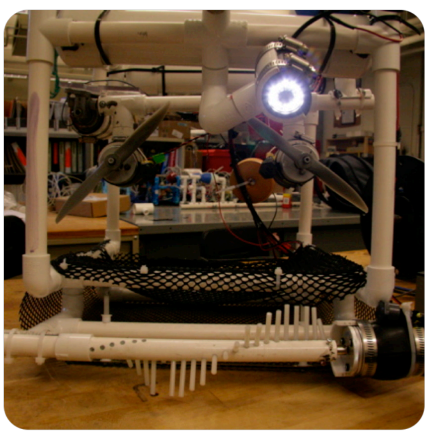
One team's ROV, with extending arms that reach out and scoop materials into the a collection basket in the body of the ROV.



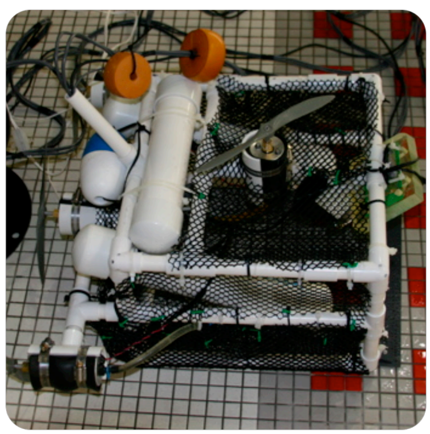
A clever solution to surfacing the ROV - using a remotely deployed inflatable vest to increase the buoyancy of the ROV.



Another method of collecting underwater materials: rotating flaps to scoop materials into the body of the ROV.



Another form of rotating scoops to bring materials into ROV body.



Difficult to see in this photo, but this ROV had another form of material collection: using a ramp to have objects slide into the collection basket in the ROV

Figure V-2: Pictures of Student Designs from *Fundamentals of Engineering: Explore Sea, Space and Earth*

Another aspect of the course that could have contributed to the development of creative thinking skills was exposure to several viewpoints within engineering. The teaching staff of the course wanted to introduce students to many perspectives within engineering. Students heard lectures from around eight professors: the four main professors of the course, a lecture on sketching from Professor Ernesto Blanco in Mechanical Engineering, a lecture on space exploration from Jeffrey

Hoffman in Aero/Astro, a lecture on ocean exploration from Professor David Mindell and a panel of engineers talking about ethics and societal implications of engineering. This was intended to broaden students' experiences within engineering and the class, and to facilitate conversations on aspects of engineering that students may not have previously considered. These conversations from lecture were continued in lab. Within the class itself, students gave two presentations over the course of the semester to receive feedback on aspects of their design. Peers were encouraged to ask questions and offer comments to the presenters to allow students to see their own design work through other people's eyes. This was also a common lab activity during the semester: students sat down with lab instructors and their teams for design notebook reviews, again to get feedback and have conversations that would help shape and inform their design processes.

Students not only gathered feedback from those around them, but also were encouraged to reflect internally upon their own design process. They kept design notebooks over the course of the semester chronicling their work and often considering how they made their design decisions. In addition, at the end of the semester they submitted a reflection piece in their online design portfolio where they were tasked with thinking critically about how their design process. These requirements are akin to the journaling discussed in the design literature (Richards 1998; Korgel 2002).

Toy Product Design

Toy Product Design requires students to build alpha-level prototypes in small teams over the course of the semester. Similar to *Product Engineering Processes*, the overarching rhythm of the course is a cycle of research, ideate, design, build test. The enrollment for the class has reliably doubled each successive offering of the class, the most recent offering of the course in Spring 2008 had forty-four students. Of these students, twenty one were male and twenty three female. Typically, there are more female students than male students enrolled in the course.

Toy Product Design students are given a specific theme or subset of toys each year. In Spring 2008, this theme was "toys that teach science and engineering." In the past this theme has included "toys that promote dental hygiene" and "toys for inexpensive manufacture in Brazil." Students brainstorm independently at the beginning of the semester to come up with ideas that suit the theme. They then develop these ideas in small groups to rough exploratory prototypes, also known as sketch models, with the aid of a graduate student lab instructor. Midway through the semester, the small groups are rearranged to put similar ideas on teams together. They then select down between the several ideas on their team to advance two to refined models, and narrow down to one turn into an alpha level prototype as a group.

There were no limits imposed on the students as to what they explore for their product concepts; students are encouraged to go out and learn about how to execute whichever idea they find most compelling. When teams lack familiarity with specific technical aspects of construction or design the lab instructors and course staff will often try to find mentors who can help guide the students or educate themselves on the subject matter so they can be of assistance.

Design Project

from left to right by row:

Cell Slap - a card game that teaches cell functions

Cool Pool - a set of modified pool balls to teach physics through intuition

LUX - an LED color-mixing dinosaur that teaches color addition

the Orb - a single wheeled motorized skateboard

Infection - a board game that teaches the functions of the parts of a cell

Electroplushies - a connectable plush toy to teach the functions of basic circuit elements

Seismic Survival - a mini earthquake table game to test the resilience of various structures

Tube Racers - racing discs that move along a tube

Electros - a light up board game to teach about circuits

Figure V-3: Photos and Descriptions of Toy Class Products 2008 (photo credits: B. Kudrowitz and M. Rush)

The end result of *Toy Product Design* are working, alpha-level prototypes of toys that fit within the course theme. Examples of these toys are shown in Figure V-3 above. This course theme, along with a small budget of $500 are the only limitations placed on the students during the semester. Students begin work on this project by brainstorming several ideas for theme-appropriate toys. They do this in lecture as a group, then build off of this by working on some independent idea generation outside of class. This second group of ideas is refined by the students after discussion in their lab sections and poster presentations to the class of the concept. Students each build a sketch model exploration of their design concept to present in lab to the group of lab instructors. Based on these sketch models, students are reassigned lab groups with similar toy product concepts grouped together. These new groups are in fact teams, as students are expected to work with one another from this point of the semester onwards. These teams of students select two ideas amongst the three to five ideas within their team to develop further, through discussion, voting and the creation of Pugh chart. As a group, they develop higher level models of these two ideas, receive feedback from their peers; instructors; local product designers and engineers; and children from the community, then choose one to develop to the final alpha prototype model.

The culmination of the semester is a presentation at the "Playsentations" event in the last week of the semester. Members of the student body, local engineers and designers, local toy designers and even students' families join the course members and teaching staff to watch students give entertaining, playful presentations of their toy product. Students are encouraged to be creative and unconventional in their presentation design: in 2008 students wore costumers, made rap videos and performed skits as some of the presentation elements.

Lectures and Labs

Toy Product Design lectures were specifically planned to give students an appreciation of child development, prototyping, industrial design and play. Students were exposed to a variety of topics within product design as well as specialized lectures on designing toys. The concepts taught in the lectures are specifically meant to be used by the students in the design process of the toys. Rather than giving students a broad understanding of several engineering concepts, they instead were given a focused subset of topics that would help with toy product design. With the exception of a couple of guest lectures each semester the course instructor, Barry Kudrowitz, delivers all lectures. Lab instructors supplement in-class materials with advice on building and machining prototypes and specific product design concepts that might apply to an individual student's projects. During the lab times, the graduate student lab instructors and mentors addressed specific engineering, assembly, and manufacturing concepts with their small groups.

Table V-3: Syllabus for *Toy Product Design*

Week	Class Theme	Lab Topics and Milestones
1	Toys and Course Overview	No lab
2	Play Brainstorming and Innovation	Hasbro Design and Engineering Tour
3	Theme Introduction Sketching and Drawing Technique	Team Brainstorm
4	Industrial Design Drawing Graphic Design and Visual Information	Concept Selection and Poster Design
5	Finalizing Posters Idea Presentation	Shop Safety
6	Sketch Model Techniques / Shop Safety Sketch Model Techniques / Shop Safety	Sketch Model Construction
7	Estimation and Energy / Sketch Models Estimation and Energy /Sketch Models	Individual Sketch Model Presentations
8	Design Aesthetic User Experience	Concept Selection
9	Skills Week - Solidworks, Photoshop Skills Week	Sketch Model 2.0 Construction
10	Design Consulting Design Consulting	Prototyping
11	Plastics and Manufacturing Prototyping	Prototyping
12	Presentations and Packaging Presentations and Packaging	Prototyping

13	Presentation Prep Presentation Prep	Presentation Prep
14	Practice Presentations Class Wrap Up	Playsentations

Students meet in small groups during the lab sections and work individually for the first seven weeks of the semester. At that point, the small groups are shuffled and students get new lab instructors and move into team-based projects. Again, this facilitates interaction and multiple inputs for student projects over the course of the semester.

Grading and Deliverables

Table V-4: Grading for *Toy Product Design*

Class Participation	Individual	15%
Lab Participation	Individual	15%
Brainstorming Assignment	Individual	5%
Idea Presentation	Individual	5%
Individual Sketch Model	Individual	5%
Team Sketch Models	Team	10%
Final Presentation	Team	15%
Final Prototype	Team	20%
Design Journal	Individual	10%

Students were expected to maintain design notebooks over the course of the semester documenting their work. These design notebooks were reviewed at multiple points during the semester by the lab instructors and submitted at the end of semester. Every other deliverable for this class was in the form of a design review for the project. Each deliverable was in the form of a physical object – a set of sketches, a poster, a model – and a presentation, either in lab to teammates and lab instructors, in class to all students and instructors, or at the end of the semester to the community at large.

Creativity Specific Aspects

Development of creative thinking skills was one of the learning goals of the course, so several aspects of class were specifically intended to nurture creative thinking within the students.

Like *Solving Real Problems* and *Product Engineering Processes* there are indications of a "community of practice" present within *Toy Product Design.* There were several layers of experience with in the teaching team of the course: a veteran professor, David Wallace; a PhD student who had designed and founded the class, Barry Kudrowitz; eight graduate student lab instructors; upperclassmen undergraduate student mentors, and even upperclassmen teammates on many of the teams. Each of these different experience levels could spend time mentoring the students and learning from one another. This teaching team also had a strong sense of community with each other, which helped give the whole class a sense of community as well. The course instructors hoped that the informality between members of the teaching staff and with the students would help students to feel more comfortable expressing their ideas in class and pursuing courses of action that may have more risk associated with them.

As for the design project specifically, toys or entertainment allow students to come into the class already with some domain-specific skills: most students have played with toys and are generally familiar with many of the toys that exist already. They can usually draw upon their own experiences to come up with new ideas in this realm and thus have a sense for what might be popular or novel. There are no conceptual limitations placed on the students aside from the overall course theme, and this meant more to serve as an inspiration or starting point rather than a constraint. If a student were to come up with an idea that he or she was excited about, the course staff would be more likely to come up with ways in which it fit the theme rather then to discourage the idea. Even a student's knowledge base is not seen as a constraint: for students working on concepts unfamiliar to lab instructors lab instructors often go out of their way to familiarize themselves with new material and find additional resources for the students.

There are also several class activities meant to aid students in their development of creative thinking skills. In the lecture on creativity and ideation students do two brainstorming activities: a warm up where students are given a topic not specifically related to the theme that is purely for fun and practicing brainstorming technique, and a second brainstorm specifically on the theme. In lab that week there is a follow-up doing smaller brainstorming session with up to five students and their lab instructor and mentor. This is the first of several brainstorming sessions in lab, the scope of the brainstorming sessions get progressively narrower as students refine their ideas.

With regards to domain-specific hands=on skills, in the first week of lab students are familiarized with the machines in the shop through a small design-and-build project. Students are asked to design a small pull-toy similar to what they may have played with as a child. Then students use the machines in the shop and a set of stock wood to physically build their design. Though this is more a practice of aesthetics design than mechanics, it still requires use of the band saws, belt sanders, drill press and a variety of hand tools. Students get to keep their pull-toy as a take-away of the machining lab. This give student the creative experience of designing something pleasing to them and the physical experience of building it to their own specifications.

Reflections on *Explore Sea, Space and Earth* and *Toy Product Design*

The use of course webpages and class e-mail lists make it possible for students and teaching staff to have round the clock and immediate communication. Both *Fundamentals of Engineering* and *Toy Product Design* used new media heavily over the course of the semester. Each course had a class website that housed class-related resources. For *Fundamentals of Engineering*, a course webpage hosted on MIT's standard course management system was used to post the syllabus, lecture materials and readings. In addition, each student was expected to prepare a web-based portfolio of his or her design process chronicling the design process by the end of the semester. For *Toy Product Design* the website was designed and maintained by the course instructor Barry Kudrowitz. Again, the website was used to disseminate the syllabus, as well as suggest course-related readings and an updated slideshow of the students working during the semester. In addition the *Toy Product Design* class often gave assignments that could be much improved with the knowledge and understanding of some basic design software. Additional voluntary workshops were held on weekends to familiarize students with Photoshop, Keynote, Solidworks and Dreamweaver.

Each class also familiarized students with machining and fabrication techniques in the shop very early in the semester and with heavy mentoring from the lab instructors and mentors. With first-year students in particular, as made up a majority of these two classes, these hands-on workshops giving students practice in making reality of their ideas can be crucial in letting students express their creativity. Csikzentmihalyi (1988) and Gardner (1993) often discuss the importance of the acquisition of domain-specific skills in the development of creativity. First-year students often lack the practical knowledge and experience of physically building or developing projects. Giving inexperienced students a safe environment where they can experiment and learn in the presence of direct mentors allows them to cultivate these domain-specific skills.

An important aspect of each of these classes is the amount of resources they require to plan and sustain. Each of these classes used a dedicated lab space complete with machining areas and benches for student work. However, it is possible to share lab space with others, it requires that students work on projects small enough to transport and store in between class sessions. For each of these two classes this was necessary regardless: there were multiple lab sessions, so students had to move their materials away from the lab bench when they were finished. Notably, in the first two years of offering *Toy Product Design* the instructors worked exclusively in lab and shop spaces shared with other classes and student clubs.

These two classes also require considerable numbers of instructors and teaching staff: four professors and three teaching assistants on *Fundamentals of Engineering* and two course instructors, eight lab instructors and eight mentors on *Toy Product Design*. Fundamentals of Engineering reduced in teaching staff the second year of its offering, and *Toy Product Design* relies on volunteers. This require a lot of legwork on the part of the course instructor before the semester starts in order to recruit a team of mentors and instructors who are willing to volunteer their time. One inducement that can be used for the undergraduate students is to offer them course credit in exchange for their time.

Lastly, these courses require a fair amount of monetary resources to buy materials for the students. One way *Toy Product Design* managed with a smaller budget was to assign a course theme that aligned with a small budget: toys for low-income manufacturing. *Fundamentals of Engineering* manages a smaller budget by limiting the materials students use to construct their design projects to PVC and zipties. The rest of the components of the ROVs can by reused from year-to-year, distributing the cost over several semesters.

VI. Discussion and Analysis

The literature about creativity in engineering make clear that creativity is a desirable characteristic of engineers in the workforce. It is recognized a driver of innovation in organizations and a success factor for industries and corporations. As such, the creativity of engineers is highly valued. One of the responsibilities of higher education institutions is to prepare their students by helping develop skills that are highly valued by society, and creative thinking is a transferable skill that certainly falls into this category.

This thesis profiles four classes spanning all years of MIT undergraduates, and representing a range of engineering and science departments, though mostly Mechanical Engineering: *Solving Real Problems*, *Product Engineering Processes*, *Fundamentals of Engineering: Explore Sea, Space and Earth*, and *Toy Product Design*. Across these four classes, a majority of the students indicated that they believed that their creative thinking abilities had increased over the course of the semester: 85% of the students in *Solving Real Problems,* 25 out of 42 respondents, or 60% for *Product Engineering Processes*, 87% of respondents for *Toy Product Design*, and 65% of respondents for *Fundamentals of Engineering*. There are some clear common ties between the classes and lessons on developing and sustaining these types of courses at higher education institutions.

Themes Connecting *Solving Real Problems, Product Engineering Processes, Fundamentals of Engineering* and *Toy Product Design*

One theme that echoes through all of the courses profiled in this thesis is the importance of classroom environment and classroom community. The experiences of the students in *Solving Real Problems* show that course culture and relationships with professors and teaching staff hold a prominent position in student's memories when asked about the creativity development after a class is finished. In the *Product Engineering Processes* data the relationship between team assessment of creativity and individual assessment of creativity are clear and significant, showing that students from teams they believe to be more creative feel as though they themselves have had a greater increase in their creativity over the course of the semester. In both *Toy Product Design* and *Fundamentals of Engineering*, the teaching staff highlighted the importance of class community and feedback. All students in each of these four courses observed and participated in design reviews, allowing them to both learn from their peers' work but also letting them contribute to the development process of other teams. Each of these classes were also structured to fulfill a communications requirement, meaning that as students participated in peer reviews, there were communications instructors to help them improve their abilities to convey their messages in a constructive fashion. Each of these classes made clear that the community of the class extended beyond the boundaries of the classroom walls: guest lecturers were invited to speak and participate in design reviews and *Solving Real Problems*, *Toy Product Design*, and *Product Engineering Processes* all required that students work with community partners over the course of the design process.

In the student interviews of *Solving Real Problems* and the course structure of the other three classes another powerful theme was the practice of skills, both in creative thinking and also in activities that allow students to become confident in their abilities to bring their ideas into reality. Each class addresses machining and design early on in the semester, and a particularly interesting example of this is the cardboard chairs activity. Typical beginning machining exercises require students to follow a cookie cutter pattern on the machines. However, both *Toy Product Design* and *Solving Real Problems* include an element of design to their introductory machining exercise, which allows students to feel more ownership of the activity and also begin to see what it is like to take a design that only exists within their brain or on paper and turn it into a physical object. Building confidence in these skills is something that seems to be particularly important for females in engineering, as the data from *Solving Real Problems* shows.

Related to the theme of hands-on practice, each of these four classes taught the basics of creative thinking: brainstorming skills, an element of reflection and prototyping and testing. However, most of these classes went beyond holding lectures on these topics to actually practicing these skills with the students. In essence, the *Product Engineering Processes* data shows that time on task, or time spent brainstorming, does not in itself have a strong correlation with change in creative self-efficacy. However, the stories from *Solving Real Problems* suggest that time spent brainstorming with role models of creative thinking who actively demonstrate divergent thought in front of the students can be a powerful inspiration to students. The suggestion from this combined set of insights is that it is quality, not quantity, of brainstorming time that can influence creative self-efficacy. In some cases, this may require the teaching staff to model brainstorming and divergent thinking for the students so that they can feel comfortable expressing their ideas without internal judgment. Care has to be taken to ensure that the relationship between professors and students does not inhibit student expression, but given the data from these courses this seems like a feasible task.

The data from *Solving Real Problems* and *Product Engineering Processes* also suggests that team assignment can be a significant factor in student's self-assessed creative thinking ability. Dedicating teaching time or class resources towards working on students' teamwork skills might be valuable in affecting students' perception of their creative thinking skills. Interestingly, *Product Engineering Processes* assigns students to teams randomly, while *Solving Real Problems* drew individuals together through common interest in a particular project. *Toy Product Design* functions similarly, grouping students into teams by uniting ideas with common themes or roots. *Fundamentals of Engineering* on the other hand, let students self-select into teams of their choosing resulting in groups of friends choosing to work on teams together. Each of these different methods has its strengths and weaknesses. Regardless of the method of team assignment, students are bound to face challenges in working together and it may help student creativity to acknowledge this early on in the semester to provide students with the tools to effectively negotiate situations and foster a creative working environment.

Implementation Challenges and Supportive Policies

A common challenge across each of these four classes was assembling the resources, such as staffing, budgetary, and facilities, in a manner that is sustainable from year-to-year. These classes rely on low student-instructor ratios because of the amount of time that is spent in small design groups or hands-on instruction. One successful method that a few of these classes have employed is recruiting engaged and passionate upperclassmen and graduate students to volunteers as mentors and instructors on the class. This method is particularly effective in "community of practice" style classes, since they will also have the chance to treat the course as a learning experience and receive mentorship from those more experienced in the content matter. In order to keep this sustainable from year-to-year *Toy Product Design* and *Product Engineering Processes* make a point of recognizing the volunteers' work at the end of the semester. Also, it highlights the importance of building a community around the class that both the teaching staff and the students enjoy being a part of. This recommendation goes hand-in-hand with making sure that the topic of the class and the specific design projects are ones that a significant number of people find interesting and fun. Though *Toy Product Design* and *Product Engineering Processes* both require a large number of volunteers, there typically are only a few that really need heavy recruiting to join the teaching staff of the class. Since the topic matter and the teaching approach are fun in *Toy Product Design*, many people are excited to be involved. Similarly, with *Product Engineering Processes* many projects deal with interesting unmet needs, providing the opportunity to be involved with a project that is truly innovative. This also eases the challenge of recruiting volunteers.

There are a number of things that institutions and departments can do to support and foster these types of design course. Clearly, a challenge for the planners and the teachers of these classes is locating resources, and a simple and obvious start would be to provide resources to these classes. The four courses in this thesis rely on outside sponsors, both industry and grant-writing foundations, in addition to departmental support. Suggesting creative ways around budgetary challenges, such as encouraging classes that address the needs of developing or low-income communities can engage students in meaningful projects that have inherent budgetary constraints.

Beyond resources and support, departments and institutions can foster these classes using other policies. Encouraging experimental classes to try out non-traditional methods of teaching is one method. Many engineering departments are encouraging first-year classes that introduce students to engineering and design in a fun manner: MIT and Tufts are examples of this. Classes such as these can recruit new students to the engineering discipline, and encouraging these courses to be incorporated into upper level requirements or electives can help keep students engaged in the practice of engineering and design. Drawing on the energy and fresh perspectives of graduate students new to teaching can bring new methods and styles of teaching. This can be encouraged through teaching development workshops, particularly ones that involve precisely the methods of teaching described in this thesis: beyond the typical lecture format and providing opportunities for experienced teachers to mentor students in their teaching.

Limitations and Future Work

One limitation of this work was my presence as an instructor or teaching assistant on each of these classes. Though this does give the advantage of having insider knowledge of the class and a pre-established friendship with the students, this study might benefit from an outsider who was not as involved with the day-to-day workings of what was happening in the lab or in the classroom. Ultimately, the added benefit of knowledge of the workings of the classroom outweighed reservations about the potential bias introduced in the data. For this reason, I have been upfront about my involvement with each class and let the reader decide how they want to interpret my interpretations of the data. Another limitation was the process of mining data rather than constructing experimental tests on students. It is difficult to set up experiments on students in the classroom without the concern of limiting the learning the experience of a subset of the students.

It may be worth studying another class that was originally planned on the "community of practice" (Lave and Wenger 1991) model or a population of students outside of MIT, unlike the courses profiled in this thesis. This would help elucidate whether these themes are specific to these classes or groups of students, or if they are transferable. Equally important would be further research as to whether these skills are valued outside of the classroom, and whether this model could be scaled up to classes of a larger size. Interviewing the professors of the classes could provide information as to the professor's goals for the students and their views, or lack thereof, of the "community of practice" (Lave and Wenger 1991) present in these classes. Lastly, a longitudinal study using student journals or observation to evaluate student creativity might clarify how student perceptions of their creativity change over the course of the class rather than simply a pre-post test.

Concluding Thoughts

Engineers identify creative thinking skills as a necessity in their profession (Klukken 1997; Magee 2004). Given creativity's importance to innovation and growth of an economy, finding better ways of teaching creative thinking skills to undergraduate engineers. As a for how this will change in the near future, The National Academies state that creativity in engineering will be even more important in the twenty-first century (National Academy of Engineering 2004). The work in this thesis shows the importance of course culture, team dynamics and relationships with the teaching staff to the development of creative thinking skill in undergraduate engineers. Hopefully, future work in this field and in the practice of educating engineering students, instructors will pay equal attention to these factors as they do to lectures on brainstorming, creative individuals and patents.

Appendix A: Students' Perceptions of Creativity

In my interviews with the students of *Solving Real Problems* I wanted to understand through the students' eyes how they were defining and viewing creativity within themselves. When they told me that they felt that their creativity had developed over the course of the semester, it helped to get some context as to how they were measuring and assessing that. In this appendix is the collection of student responses to the two questions: "How do you define creativity?", with the follow up question "What about in the context of *Solving Real Problems*?" and the second question "How would you characterize MIT students' creativity?" These are verbatim transcriptions of student responses to these questions, transcribe from tape recordings with pauses and "ums" included.

	Definition of Creativity	Characterization of MIT student's creativity
Melissa	I think creativity is first of all doing exactly what we did which is taking a problem and somehow just finding a plausible solution. But also just thinking of it in a way that normal people wouldn't. You can always make a complex device, but how are you going to combine all of the needs of, all of the things you need to solve a problem for. It's easy to magnify something, we already have that out there, it's easy to light something, we already have that out there but how are we going to combine the two and make it light and make people like it. I think that's creativity, because instead of making a huge contraption where the whole table would be taken up we find something that is just small and all compact into one.	I was uh surprised that uh, I thought there would be more creativity within my group but there wasn't. And uh …That just happens. I think that almost everyone at MIT could think of a solution, but I don't think everyone has the ability to think of a solution that would work. I mean there's two steps right: there's thinking of a solution, and thinking of a solution that works. And I think that anyone could get past the first step, but not everyone, I mean even in the whole world, I think MIT is smarter because they can get past the first step. But getting past the second step, I don't think everyone at MIT can do. But that's what the class teaches you to do, so…
Adam	Just your ability to make new things I guess. *So are you speaking of things that are new to society, or things that are new to your own mind?* Well, it has to be your own mind, I guess. It could exist otherwise. You could be basing it off of other ideas that you know, but it's like a new application at least.	Um, I don't know I feel like it's not really pushed in the first few semesters so it's kind of hard to judge right now. I feel a lot of the classes are very structural and not really pushing the creative side as much, not as much as they should be

Tom	Creativity is just the ability to think outside the box. The ability to take different types of information and combine into a type of thought or a type of project or something differently. For example, just being able to do something repetitively isn't really creative, but the ability to get any type of project, to be able to pull different things from nowhere and make something is creative, to be able to write something out of nowhere is creative, just that's it.	They're very creative, it's just different types of …everybody's different in how they're creative. Because you have people who are very ingenuitive, like I know a person on my hall who is in 2.009 now and just … I was trying to fix a nerf gun and he's like "we're missing this little spring, so he pulls out a pen and pulls out the little spring, adjusts the little spring so it fits and I mean, They can take a problem and find some sort of way to fix it. My speaker broke the guys took my entire speaker apart and were like what's broken, figure it out, find any way to put it back together, make it work. And it worked again, pretty impressive. I mean, They also write, draw, paint, lots of music. MIT students are creative like in every way possible.
Jessica	Creativity: the ability to think of unique solutions and concepts in various situations and know how they would apply and bringing all of your experience previous into a certain situation and really making it your own.	They're a lot more creative than the outside world gives them credit for. I think that experience is definitely something that… I think we think up great things but in application I'm not sure that we always know the best creative ideas to use.
Allison	I think it's… to me it's the ability to fill empty space. So if there's a hole of any kind whether it be in knowledge, or in…. basically if you need something done or need to know something, there are gaps and a noncreative person might be brilliant, but if they're not creative then they can't figure out ways to fill in the gaps, they can only work with what's already known. I think creativity is the ability to fill in the gaps and then push past what is known into new territory.	I feel like there's a really big disconnect between like intellectual capacity and creativity. So some of the people I know who don't do well in their classes are also some of the most creative people I know. I think that you have these people who have won all these math competitions and done all this, you know, cool science fair stuff and whatever. And they come here and they do fantastically in all their classes but ultimately they just can't… they could only work with what they're given. And they can work with it really well but I'd say that I don't want to say that there's an inverse relation between how well you're doing in your classes and how creative you are but it definitely seems…it kind of seems like that I guess. It kind of seems like people who stand out as amazingly brilliant in their classes tend often to be the less creative ones.
Jon	Creativity kind of cliché, but thinking outside the box	I don't know. I'd say kind of uh…kind of wanting. I mean I took 2 group work classes last semester and I'd say that it's something I kind of saw in other groups … I could see it in my team members, I could see that they were creative.

Emily	I guess creativity would be like thinking outside of the box. Like there are two forms of creativity – thinking completely outside of the box, and coming up with something that no one has thought of, or combining ideas that people have come up with into something completely different, make it like a new idea.	It varies, I think it depends on the student. Some students are really creative. And It also depends on the area. Because creativity manifests itself differently depending on what department you're in or not even what department but what specific area you're working on and what you're trying to find a solution for. So like I think MIT students tend to be creative in what interests them the most and what they're specializing in, and maybe not as well in other areas
Valerie	Creativity is thinking in a new and different manner. It is taking the simplest things and seeing them in a new light. This is not anything to grandiose or anything.	I would classify them as either very creative, or very robotic. Ok. In that you have uh..students who are very good at learning the formulas, applying the formulas, no emotion, no new thought and they're good at that and they can do well on exams, that's pretty much how exams are written. Then you have those students who are always thinking of new and ingenius ways to do things. So I don't know…it seems like there are very few people who are just normal.
Frank	I would say doing something that no one has done before. But then again that might not quite be true, cause everything that you do has to come from somewhere… So I guess it might be perhaps seeing things in a way that you can filter information in a way that no one has approached it.	Well I think MIT students are pretty creative. I mean, we aren't an art school, so we don't promote that type of creativity where you're out to really um show what's your mind in some other medium. But we are challenged with these design courses. Most people do like to try new things here. And just build random stuff. On the East side they do a lot of that. So I guess their creativity might be just taking risks and doing things that they dream about but may not be totally feasible or legal for that matter. So I guess it's a different kind of creativity than what society thinks of as creativity. In a product design context it really comes to what I mentioned before of distilling data in a correct way so you're building something but you're doing in it with novel methods. And uh you're taking risks with design.
Josh	I guess one way of putting it is thinking of something different. Or doing something differently than someone else might do it. You know if you can't get something to work, then trying it a different way, like a different configuration or a different process. Being able to come up with variations to solving a problem.	From what I've seen it's vast. Around here. There's all kinds of different things, different styles, everyone here is different. The creativity is sort of, the easiest way to see it is just to walk around.

Appendix B: Interview Consent Form for *Solving Real Problems*

CONSENT TO PARTICIPATE IN INTERVIEW

Solving Real Problems, 2.00b

You have been asked to participate in a research study conducted by Monica Rush from Mechanical Engineering at the Massachusetts Institute of Technology (M.I.T.). The purpose of the study is to research the learning experiences of students participating in *Solving Real Problems* 2.00b. The results of this study will be included in Monica Rush's Masters thesis. You were selected as a possible participant in this study because you took Solving Real Problems Spring 2007. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. We expect that the interview will take about 30 minutes.
- You will be compensated for this interview in the form of coffee/snacks.
- Unless you give us permission to use your name, title, and / or quote you in any publications that may result from this research, the information you tell us will be confidential.

• We would like to record this interview on audio cassette so that we can use it for reference while proceeding with this study. We will not record this interview without your permission. If you do grant permission for this conversation to be recorded on cassette, you have the right to revoke recording permission and/or end the interview at any time.

This project will be completed by June 2008. All interview recordings will be stored in a secure work space until 1 year after that date. The tapes will then be destroyed.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

(*Please check all that apply*)

[ ] I give permission for this interview to be recorded on audio cassette.

[ ] I give permission for the following information to be included in publications resulting from this study:

[ ] direct quotes from this interview

Name of Subject

Signature of Subject ____ Date _____________

Signature of Investigator ___________________________Date _________

Please contact Monica Rush at (617) 817-9088 or monicaru@mit.edu with any questions or concerns.

If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

Appendix C: Interview Protocol, *Solving Real Problems*

Interviews were scheduled with students via e-mail, and usually with me traveling to a location that was convenient for the students: near where their classes were held over a break between classes

Questions for 30 minute interviews

1. Why did you choose to take *Solving Real Problems*?
2. Thinking back on your experience in *Solving Real Problems* last semester, what skills do you feel you have taken from the class?
    a. Are there any in particular that stand out from the rest?
    b. Which skill that you feel you gained or improved during *Solving Real Problems* do you value the most*?*
3. **Do you think that *Solving Real Problems* has influenced your creative skills? If so, how?
4. *How do you define creativity *(??in the context of Solving Real Problems)*?
5. *How would you characterize MIT students' creativity?
6. *Where would you position yourself relative to your peers' creative skills? Has this changed since taking *Solving Real Problems*?
7. Thinking back on the course, are there any activities either in lab or in lecture which you associate with developing your creativity? If so, which ones?
8. Thinking back on the course, is there anything specific to the culture of the course which you associate with developing your creativity? If so, what about it?
9. Thinking back on the course, do you associate your interactions with the professors or teaching staff with developing your creativity? If so, how?
10. (Also if so) Have you used any of these creativity skills in your courses or personal life since finishing 2.00b? Can you give examples of situations in which you have used these skills?

Appendix D: Team Review from *Product Engineering Processes*

Athena user name: __________@mit.edu

Section:

How many client/customer representatives your team has worked with? _____ [ ] I don't know

How many hours has your team has spent working directly clients/customers? ___ [ ] I don't know

Please indicate your level of agreement with the questions below.
(Disagree Completely/Disagree/Disagree Somewhat/Agree Somewhat/Agree/Agree Completely)

1 Each person on my team makes suggestions about what our goals should be.
2 Each team member contributes whatever he or she can to solve a conflict when one occurs.
3 Each of my fellow team members is fully aware of the entire team's task requirements.
4 My team members know that different situations require different decision-making styles.
5 On my team everyone is willing to help everyone else.
6 On my team decisions are discussed, issues are understood, and the team attempts to get consensus whenever possible.
7 My team is a very creative team when required to be.
8 My team is always aware of how well it is performing.
9 My team or task force stays together until it finishes each task.
10 My team has learned to put personal agendas aside in favor of group goals and cooperation.
11 My team is able to reduce or eliminate most of the problems that arise in connections with our work.
12 Each team member respects the skills of all other team members.
13 My team's communication with one another is open and candid. Team members talk freely, sharing true feelings.
14 Team meetings are highly productive and are conducted in an efficient and a time-conscious manner.
15 My team changes its goals when it must respond to a new situation.
16 When work gets backed up, members of my team pitch in to eliminate the backlog.
17 Members of my team are inclined to point out conflicts and constructively deal with them.
18 Team members listen to one another and respect the viewpoints of others, even when they don't agree with the team.
19 My team permits me to be the leader when I have special expertise about a task.
20 My team is fully aware of the end results we are trying to achieve.
21 My team often reviews progress and agrees on actions to improve the way we function as a group.
22 My team has a good balance between getting the work done (tasks) and improving our teamwork (process).

23 All team members know how to provide feedback to each other.
24 My team's leadership is very effective in helping members to work together in achieving team goals.
25 I am willing to stop doing my task if another team member needs help.
26 I am able to see things from different perspectives to overcome stale thinking within the team.
27 I am aware of the impact that my actions have on others in my team.
28 I am committed to completing the tasks that my team or task force is currently accountable for.
29 I am unconcerned about status amongst my team members.
30 I am in agreement with the goals of my team.
31 I am constantly looking for ways to help my team use resources efficiently.
32 I use a variety of approaches in helping my team resolve conflicts amongst team members.
33 I have knowledge about what each team member is doing when we are working on a project.
34 I am skilled at giving my team members specific feedback.
35 My team members take ownership for each others' performance and will contribute whatever it takes.
36 My team members always consider the positive and negative aspects of each new idea.
37 My team members want to fulfill all task requirements before leaving.
38 My team members are willing to listen if someone has an idea about how to improve individual performance.
39 My team members are far more productive as a group than they would be if they worked as individuals.
40 I feel included whenever my team discusses goals.
41 I take advantage of all the resources my team has at its disposal.
42 I never walk away from a team disagreement without getting it dealt with.
43 I believe that each team member provides leadership at one time or another.
44 I have a sense of what each team member does regardless of the task we are working on.
45 I am comfortable with telling people outside of my team how my team is performing.
46 I always help my team members succeed.
47 I feel that my team members are able to be flexible when considering how to get something done.
48 I am able to evaluate my contribution to successful team goal accomplishment.
49 I feel a sense of togetherness amongst members of my team.
50 I have useful ideas that my team members will listen to because they want to maximize performance.
51 I understand our mission and the goals and standards our group is expected to meet.
52 I am very good at working in a team.

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