1st Annual CDIO Conference
Queen's University
Kingston, Ontario, Canada
June 7 to 8, 2005

PRODUCT DEVELOPMENT BY DETERMINISTIC DESIGN

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ABSTRACT

In the MIT Mechanical Engineering course, Introduction to Design and Manufacturing (2.007), students learn Deterministic Design, a design process similar to the scientific method approach to solving problems in the natural world. Deterministic Design merges qualities of the scientific method with the business focus of risk assessment and countermeasures, and schedules. We call it Deterministic Design because the method seeks to minimize unknowns, and to map out a solution path and implementation plan. We practice it with the use of a Peer-Review Evaluation Process (PREP).

Idea development is a sequence of three stages: Strategies, Concepts and Modules. At each step of creating (strategy, concept, and modules) a deterministic process occurs. Individuals create (and write down their ideas), PREP, and then brainstorm. It is with this crucial process, we can virtually guarantee underrepresented people will be drawn in as fully contributing members of design teams.

Individual Thought constitutes the first phase during each of the three stages of developing ideas. During the second phase in developing ideas, a peer-review process is employed, where (N) people circulate their Milestone Reports to the other (N-1) people for comments. Brainstorming is the third phase, which helps teams solve personal creativity deadlocks and helps to ensure nothing has been overlooked. Collectively, we call these three phases the Peer-Review Evaluation Process (PREP). It maintains the creativity of individuals and the power of teams, and provides a written record for how ideas evolve.

PREP is not intended to add time to the design process; it is a step that is missing from the process to reduce time, by getting everyone fully involved, and to understand what team members are doing.

NOMENCLATURE

DD = Deterministic Design
PREP = Peer-Review Evaluation Process
BLE = Bench Level Experiment
FRDPARRC = Functional Requirements, Design Parameters, Analysis,
References, Risks, Counter-measures

INTRODUCTION

In the MIT Mechanical Engineering course, Introduction to Design and Manufacturing (2.007), students learn *Deterministic Design*, a design process similar to the scientific method approach to solving problems in the natural world. The so-called "scientific method"[1] generally includes the following steps:

Identify a problem

Develop a hypothesis

Design a controlled experiment

Run the experiment and gather data

Analyze the data

Modify the hypothesis accordingly

Deterministic Design merges qualities of the scientific method with the business focus of risk assessment and countermeasures, and schedules:

Observe the problem and it's physics

Develop a hypothesis/solution

Use peer-review to evaluate the hypothesis and later the solutions

Analyze the proposed solutions, and perform Bench Level Experiments (BLE)

Study references and appraise solutions to identify the "best one"

Assess the risks[2]

Plan countermeasures

Employ, examine and enhance the idea to alleviate flaws, and resort to countermeasures if falling behind schedule due to profound complexity

Because this method seeks to minimize unknowns, and to map out a solution path and implementation plan, we generally call it *Deterministic Design*, with the use of the *Peer-Review Evaluation Process* (PREP). Table 1 shows how these issues are captured in a table format that students are asked to address.

1 Scientific Method as summarized by Slocum, A., Graham, M., and Abu-Ibrahim, F., Teaching Design With A Peer-Review Process [1]. Some see the design process as being quite different from the scientific process. The scientific process leads to new understanding and the design process leads to new products. However, similar processes can be used to reach different ends.

2 For more detail than common knowledge, or gut feeling, Failure Mode and Effect Analysis, FMEA [2], or Finite Element Analysis, FEA [3] can be used to assess the risks.

Functional Requirements (Events/Actions)	A list of independent functions that the design is to accomplish.

Table 1: Functional Requirements, Design Parameters, Analysis, References, Risks and Counter-measures, also known as "FRDPARRC" (pronounced "Fred Park") coined by Prof. Alexander Slocum at MIT.

Idea development is a sequence of three stages: *Strategies, Concepts* and *Modules*. Each stage essentially requires addressing the issues in Table 1. As shown in Figure , first strategies are determined (overall approaches to solve a problem) and then concepts are developed to implement the strategies. Simultaneous consideration of strategies and concepts allows for the best concept to be chosen: the best strategy is the one that likely achieves the best performance with the most manageable risks. Afterwards, the individual modules of the project are designed. This concept of *Deterministic Design* still leaves a lot of room for the wild free creative spirit that inspires experimentation and play.

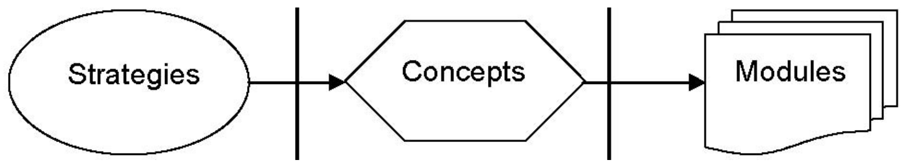

Figure 1: block diagram of the stages of idea development

At each step of creating (strategy, concept, and modules) a deterministic process occurs. Individuals create (and write down their ideas), PREP, and then brainstorm. It is with this crucial process, we can virtually guarantee underrepresented people will be drawn in as fully contributing members of design teams.

Individual Thought constitutes the first phase during each of the three stages of developing ideas. At this phase, things are done in leisure to inspire creative thought. Observations are made of what other people have created, the library/web is searched, and the best are taken from different ideas to evolve them into the best two or three ideas. The information in Table 1 is updated and *Milestone Reports* are created for the top ideas, in such a way that any random person can understand the ideas without any unwritten explanation.

Functional Requirements (Events/Actions)

A list of independent functions that the design is to accomplish.

Design Parameters (Solutions)

Each FR can have several potential DPs. The "best one" ultimately must be selected.

Analysis

Each DP's feasibility must be proven quantitatively.

References

Anything that can help develop the idea, including personal contacts, articles, patents, www, etc.

Risks

High, Medium, Low (explain why) development risk assessment for each DP.

Counter-measures

Ideas or plans to mitigate each risk, including use of off-the-shelf known solutions.

Strategies

Concepts

Modules

Overview/Order of what machine will do

Architecture of design/machine

Detailed designs of components that make up machine

During the second phase in developing ideas, a peer-review process is employed, where *(N)* people circulate their Milestone Reports to the other (N-1) people for comments. A written record is thus also made of who first had the idea, so personality conflicts are more easily avoided. No talking is allowed and written constructive comments are made on each other's papers, until everyone has evaluated everyone else's ideas. This method creates a collective mind, so everybody knows what everyone else has been thinking.

Brainstorming is the third phase, which helps teams solve personal creativity deadlocks and helps to ensure nothing has been overlooked. Initially, everyone voices their suggestions, and then ideas are distilled. If there are unknowns or great risk items, rather than endless discussions, team members are sent off to gather data and run experiments. Every decision must be made based on facts and reason, not emotion or status.

Collectively, we call these three phases the *Peer-Review Evaluation Process* (PREP). It maintains the creativity of individuals and the power of teams, and provides a written record for how ideas evolve.

A team must evaluate design alternatives and various methods are well known. The simplest is a linear weighing scheme where the list of functional requirements is used as the evaluation parameter[3]. A relative importance weight to each evaluation parameter is set, and one design is set as the baseline to which all others are compared by setting ones and zeros. Once the "best" design is found, students look at other designs that have higher weights and see how those characteristics can be transferred to the "best" design to make it even better. Evaluation of design alternatives is also compatible with QFD and other similar methods.

Many designers think they already do fundamental design with peer-review. They may complain about the time they spend in meetings, presumably doing peer-review of progress on a design. PREP is not to be used to review progress; it is a development process that ensures that the best approach is pursued, and everyone is fully contributing and taking ownership from the beginning of the project. It is not intended to add time to the design process; it is a step that is missing from the process to reduce time, by getting everyone fully involved, and to understand what team members are doing.

3 Prof. Stuart Pugh [4] took the approach that these sorts of methods are powerful, but engineers may spend more time creating matrices and evaluating options than they do creating ideas. Pugh's approach was to call for a table, now referred to as a "Pugh Chart" that lists the different ideas in the top row, and the comparison attributes or functional requirements in the left column. A baseline idea is selected, given it a score of "0" for each attribute. All other ideas are then compared giving them scores from "++" for far superior, to "+" for superior to "0" for equal to the baseline, to "-" for worse to "--" for much worse than the baseline. The "best" idea is the idea with the highest score; however that does not mean that this is the idea to use as is. Rather the goal is to then go back to the table and see which other ideas have higher individual ratings for some of the functional requirements, and then to see if their particular "++" attributes can somehow be used by the "best" idea; thus evolving the idea into a truly "best" idea. A weighted design comparison chart uses the same basic ideas as a Pugh Chart, but it includes a weighting column for weighting the importance of the design attributes. A compromise is to start with equal weights, and then if convergence is not reached, consider giving priority to some of the attributes.

Again, the prime purpose of the chart is to identify the most promising ideas, and then replace whatever deficient modules they have with better modules from other ideas.

Observations

In teaching the MIT special program SEED Academy's introduction to mechanical engineering course to high school freshmen in the spring of 2005, students were given complete control over every decision relating to their project, except who their teammates would be. In picking teams, students were randomly separated into seven groups of four students.

After selecting the teams, students were given an individual thought assignment, later to be peer-reviewed. Unlike previous semesters, the majority of the students in the class were female. It was soon realized that one of the teams had 5 members and another team had 3 members. Upon inquiring who was on the wrong team, a student raised his had and asked if he could switch teams. His request was denied and he was asked why he wanted to be moved. He expressed that he had problems working with female students and he happened to be the only male on the team he was assigned. The value for minorities of deterministic design with a peer-review evaluation process was explained to him and he was promised that as long as he and his team followed the process as explained to them, gender would not be a factor.

A close eye was kept on the team throughout the process; they never expressed any problems between them, nor were any witnessed. In fact, everyone on the team felt ownership of the design and stated their satisfaction with the team and their final product. The program administrators also gave weekly updates stating that the students indicated they were very excited about their projects and working with their classmates. Other instructors in the program, not using deterministic design with PREP, had horror stories about getting their students to work together effectively in teams.

In 2005, every aspect of the MIT Second Summer design workshop used deterministic design with peer review. The project was selected by instructors and TAs who used weighted selection to finalize on a topic from lists made individually and then peer reviewed. The topic was assigned to the students, who were given a demonstration of how to design deterministically and how to use PREP. Below are examples of projects completed by the students over the three week time span of the program.

The Ponder Puzzle is an interactive learning tool, which teaches users facts about different topics, based on the particular puzzle being solved. A puzzle of the world teaches facts about continents; a puzzle of a country teaches about states, provinces, cities, etc.; a puzzle of the human body teaches about bones, muscles, organs, etc. Figure displays a PREP sheet of one student's strategy that led to the team's concept for the puzzle.

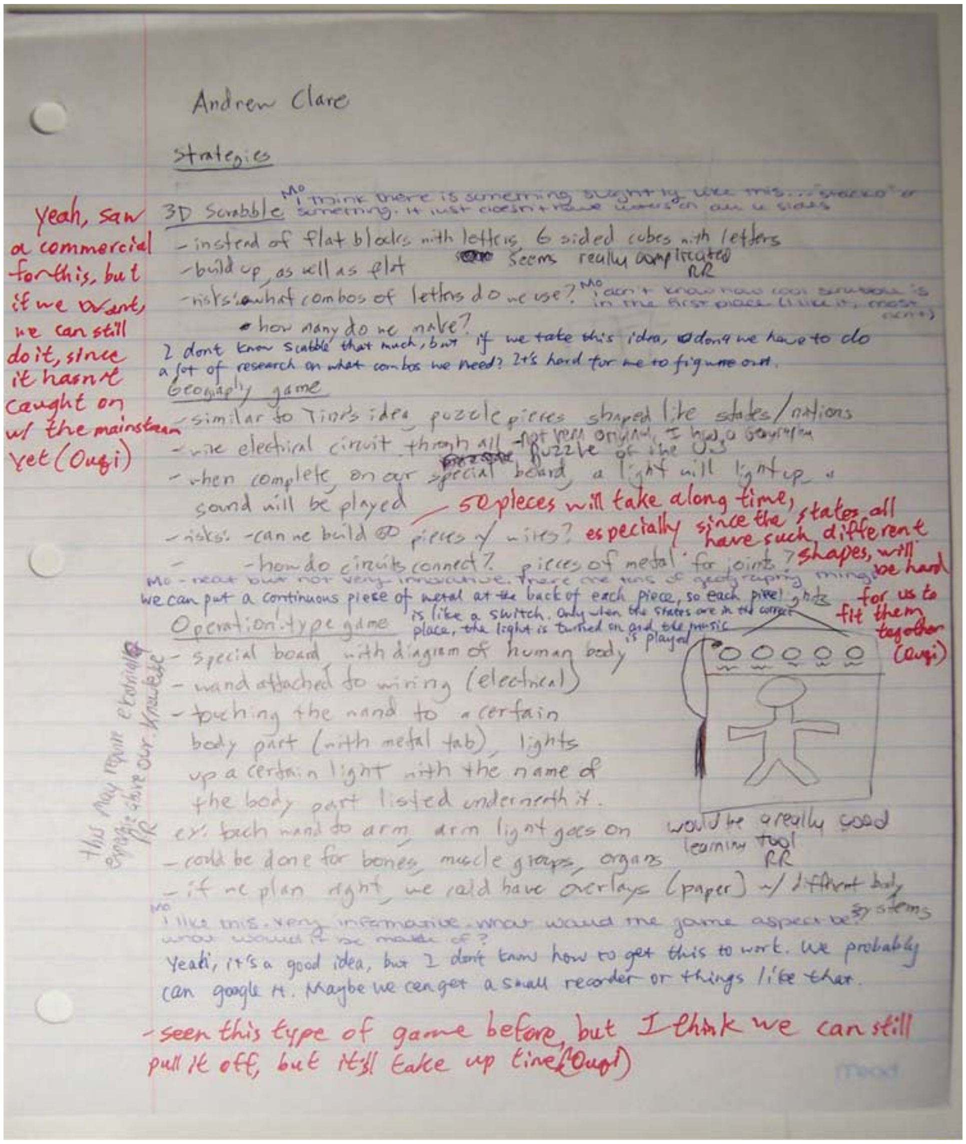

Figure 2: PREP of strategies for interactive puzzle. A.Clare, R.Rudd, M.Daniels, O.Jiang, T.Wen

After selecting a strategy for their design, the students each developed concepts and peer reviewed them to decide on the ultimate concept. Solid models of the final design were completed along with manufacturing plans, breaking the concept into modules. The students divided the responsibilities for manufacturing the modules and upon completion assembled the modules to construct the final design as seen in Figure . The final design plays a brief audio message and lights up when each piece is inserted. After the entire puzzle is completed, a more detailed audio message is played and the entire board lights up and plays a congratulatory song.

Figure 3: Ponder Puzzle – informational puzzle. Piece play audible message when placed in position. Puzzles are interchangeable, base is permanent. R.Rudd, M.Daniels, O.Jiang, T.Wen, A.Clare

Other learning tools developed include: a writing training device with a metallic plate under a stencil and a stylus that completes a circuit resulting in music being played as long as the stylus stays in contact with the metallic plate inside the stencil borders; an introduction to engineering kit that includes analysis and construction tools to be used to complete engineering challenges designated by selecting an objective card; and a monopoly-like game that focuses on car maintenance as opposed to real estate.

In 2004, Prof. Slocum and Marc Graham individually brainstormed topics from which they selected moving stuff as the theme for the Second Summer design workshop. They wanted to give the students plenty of design freedom, so they intentionally assigned a very broad topic. The students used deterministic design with PREP throughout the development of their products.

The Mo' Couch (short for Modular Couch) is modular and easily repositioned furniture. Single user seats are simply linked together to form the desired length couch. When tilted back, wheels in the rear of the chair contact the ground making it easy to move. There is also the additional feature of a newspaper/ magazine rack on the back of the Mo' Couch chair.

Figure 4: Mo' Couch – modular and easily repositioned furniture. B. Edwards, L. Hopeman, A. González, S. González, L. Fouché

Other designs developed for moving stuff include: a toddler tray with latches for locking down specially equipped bowls and cups, so they cannot be thrown from the tray; Flip-flops with a flexure design allowing them to be folded and placed into a case for clean transport in a handbag; an under-the-bed, in-the-closet, or wall-hanging shoe tram that turns through a selection of shoes, allowing the user to rest in one position and pick the desired shoes once they are in the front position; and a laundry transport rolling cart, equipped with sections for separating laundry as necessary.

Two patents[4] have been issued for products developed using this process, and one is pending. The next step is to bring this process to other schools for evaluation and possible adoption. Introduction has been initiated by implementing the process in MIT hosted design programs. One book of poetry and a music CD[5] have been created through the application of a derivation of this process, demonstrating its versatility. In addition, a large amount of technical projects have been completed using Deterministic Design and PREP as part of Prof. Slocum's Precision Machine Design course (MIT course 2.75).

Due to a lack of resources (shop space, machine tools and construction materials) it is often difficult to teach project based design in underprivileged communities. Marc Graham developed the *Creative Deterministic Composition* writing process as a means of teaching the design process without the need for shop space, machine tools and construction materials. The only resources necessary for creative deterministic composition are writing space, writing tools and words.

Marc Graham's personal experience and work with teens have alerted him that many underprivileged youth have a fondness for rap music as a form of creative expression. For this reason, he selected rap music as his basis for teaching creative deterministic composition. In the spring term of 2005, he taught a pilot course to MIT students in creative deterministic composition. Throughout the semester, the students wrote raps using the creative deterministic composition writing process in teams.

Midway through the semester, he suggested the students present their work at an event heavily populated by minority students and the non-minority students expressed discomfort and an unwillingness to present. Since the event was not stated on the syllabus, he did not require them to attend, though he mentioned to them that the discomfort they felt was the same discomfort minorities feel when they must work as part of a "diverse" team. It is difficult to assume an empowered or leadership position in an environment where one is regarded as an outcast. The creative deterministic composition writing process and deterministic design with a peer-review evaluation process have been found to be very effective in addressing the discomfort felt by minorities on "diverse" teams.

In addition to the three courses referenced above, Deterministic Design with PREP has been used in several other courses including the MIT sophomore mechanical engineering course Introduction to Design and Manufacturing (course 2.007). Course descriptions for other courses where Deterministic Design with PREP was used can be found in the appendices.

4 US Patent# 5,915,869: Ergonomic Cleaning Apparatus With Multiple Scrubbing Surfaces and US Patent# 6,641,453 B1: Construction Set For Building Structures.

5 Journey of The Lost Souls, by Marc Graham www.jotls.com

CONCLUSIONS

We have found that having some engineering background prior to learning Deterministic Design with PREP facilitates its use in engineering design work. Math and science training hones the brain's skills to think rationally, which is needed to add to shear creativity in order to complete a design and bring it to market. Students having only completed calculus and physics are able to use Deterministic Design with PREP, but not as effectively as students who have had calculus, physics and some engineering courses. Students that have taken engineering courses and/or have some design experience, as well as students without experience in engineering problem solving can apply Deterministic Design with PREP after being briefed on its use. PREP is useful for virtually any project involving teamwork. Having some engineering, or design background facilitates Deterministic Design with PREP, because Deterministic Design with PREP requires *individual* work to be evaluated by *team members*; students that have been introduced to engineering problem solving and design processes have less trouble approaching design problems individually than students who have not.

Students taking the MIT mechanical engineering Introduction to Design and Manufacturing course, 2.007 and NASA RISE students are able to successfully apply Deterministic Design with PREP soon after being introduced to it. With even more experienced problem solvers and experienced PREP users, we have witnessed PREP used even more effectively. The design of the competition table for 2.007 was completed by students who have taken 2.007 and a higher level student majoring in physics. For approximately two weeks, the team of five collaborated on a table design without first completing independent thought, designing deterministically and then using PREP. Without PREP, ideas were being evaluated and pursued as they were being presented, which lead to limited designs and much repeat process. After several unsatisfactory table designs, Deterministic Design with PREP was applied, resulting in many more ideas, a progressive process and a satisfactory table design in approximately two weeks time.

MITE$_2$S students are able to apply Deterministic Design with PREP, but require guidance in Deterministic Design; their unguided approach leads to trail and error being used as opposed to Deterministic Design. Trial and error causes PREP to be inapplicable, since designs cannot be evaluated before being completed. In addition, trial and error leads to an abundance of wasted time and materials. A way to compensate for inexperience in engineering problem solving is to provide rudimentary multiple choice options to make the students' design process deterministic; before students decide on strategies, they are presented numerous undeveloped possible strategies; before students decide on concepts, they are presented numerous undeveloped approaches to accomplishing their strategies. Students select from the options they have been presented and improve upon them, as opposed to starting on their own without a reference point.

Second Summer Program (SSP) students, after only one semester at MIT, do an excellent job applying Deterministic Design with PREP and sticking to a rigorous design schedule. They require very little guidance and receive only one lecture introducing them to the project and necessary steps to complete it. Their projects however, tend to be technically simple and do not require much knowledge of machine design, unlike the MITE$_2$S students who complete the same projects as 2.007 students. In past years, Second Summer Program projects have included tasks such as toy designs, game and puzzle designs and playground equipment designs.

For best results in Deterministic Design with PREP, students should thus have an understanding of the principles involved in solving their design problem. Students should also respect the importance of maintaining a suitable design schedule. When the process is employed as intended, it should result in an increase in design sophistication and a decrease in design time. Hence Deterministic Design with PREP can be a simple enough process for any team to use, but it does require a modest level of discipline associated with wanting to work with others. Using PREP facilitates design work in teams; and we have found that reviewing the work of peers in development of designs helps PREP practitioners become better designers.

ACKNOWLEDGEMENTS

We would like to acknowledge the following programs and people for their support of Deterministic Design with PREP:

MIT Special Programs Office (SEED Academy and MITE$_2$S)

- Karl Reid
- Nicole Stark
- Sandra Tenorio

MIT Office of Minority Education (Second Summer Program and NASA RISE)

- Dean Leo Osgood
- Dean Kimberly Beamon
- Gail-Lenora Staton
- Marlisha McDaniels

MIT Mechanical Engineering Department

MIT Experimental Study Group, ESG

REFERENCES

1 Slocum, A., Graham, M., Abu-Ibrahim, F., Teaching Design With A Peer-Review Process, 2nd Annual Hawaii International Conference on Social Sciences, Honolulu, HI, June 2003

2 McDermott, R., Mikulak, R., Beauregard, M., *The Basics of FMEA*, Productivity, Inc., 1996

3 Cook, R., Malkus, D., Plesha, M., Witt, R., *Concepts and Applications of Finite Element Analysis*, Wiley Text Books; 4th Edition, 2001

4 Pugh, S., Total Design: Integrated Methods for Successful Product Engineering, Addison-Wesley Pub Co, 1991

APPENDICES

MIT Course 2.007 – Introduction to Design develops students' competence and self-confidence as design engineers. Emphasis on the creative design process bolstered by application of physical laws, and learning to complete projects on schedule and within budget. Synthesis, analysis, design robustness and manufacturability are emphasized. Subject relies on active learning via a major design-and-build project. Lecture topics include idea generation, estimation, concept selection, visual thinking and communication, kinematics of mechanisms, machine elements, design for manufacturing, basic electronics, and professional responsibilities and ethics. A required on-line evaluation is given at the beginning and the end of the course so students can assess their design knowledge. (http://pergatory.mit.edu/2.007/)

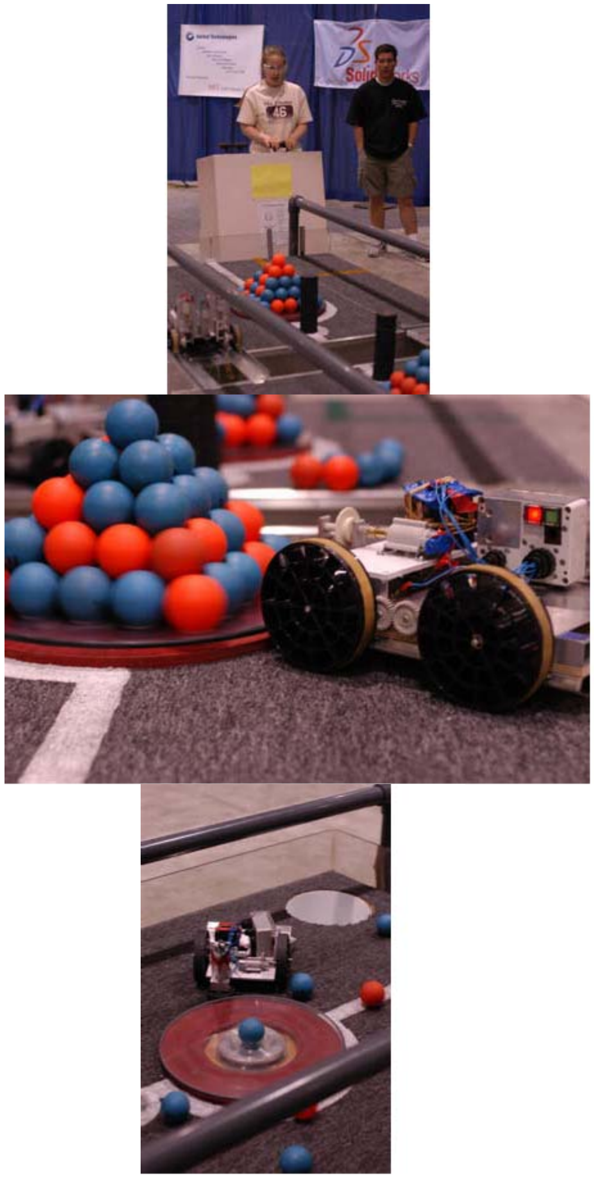

Figure 5: MIT Mechanical Engineering course 2.007, Introduction to Design and Manufacturing.

MITE$_2$S – Minority Introduction to Engineering, Entrepreneurship and Science is a rigorous six-week summer residential program for rising high school seniors who are interested in studying and exploring careers in science, engineering and entrepreneurship. It was expanded to an all-inclusive program this summer, with a more diverse group of students. (http://web.mit.edu/mites/)

Figure 6: MITE2S Program, Minority Introduction To Engineering Entrepreneurship and Science.

MIT Course 2.993 – Pathways to Peace teaches creative design based on the scientific method through the design, engineering, and manufacture of a detailed inlaid tile. This is an introductory lecture/studio course designed to teach students the basic principles of design and expose them to the design process. Throughout the course, students are introduced to the terminology and concepts that underlie all forms of visual art; which-in many ways-forms the basis for the design of all physical objects. Along with learning mechanical skills, thinking both critically and visually, and working with different media, students consider how the arts grow out of and respond to particular cultural contexts and ideas; and how these thinking patterns can be applied to virtually all types of design. Presentations, lectures, demonstrations, discussions and various artistic works are used to show students how other artists and designers have dealt with the same issues they face in lab. (http://pergatory.mit.edu/2.993/)

Figure 7: MIT course 2.993, Pathways to Peace.

NASA RISE – National Aeronautics and Space Administration Research In Science and Engineering is a program for talented college and university students focused on preparation for graduate school. RISE has always been all-inclusive but generally attracts mostly minority students.

Figure 8: NASA RISE, Research In Science and Engineering.