

# Teaching High School Students and College Freshmen Product Development by Deterministic Design With PREP

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*This paper describes an effective method for teaching design in a deterministic manner that is especially effective for under-represented students (e.g., culture, race, gender, physical disability, personality, etc.). Ten years ago we postulated that students can learn a deterministic design process not only to learn about design, but to better study math and science with peers through the use of an ordered peer-review process. The foundation of Deterministic Design is that everything happens for a reason (science, e.g., physics) and a systematic approach should be used first by individuals in a team to ask and answer questions. To ensure participation and to check that items have not been overlooked, work by individuals is followed by a Peer-Review Evaluation Process (PREP) and then the team brainstorms. Deterministic Design has designers describing what is to be done (functional requirements), how it can be done (design parameters), why it will work (analysis), who else has done similar work (references), and what are the risks and possible countermeasures. PREP is especially useful for diverse teams of designers with members from various backgrounds and personalities. It is also especially useful for enabling introverted team members to fully contribute to the development of designs.*

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## 1 Introduction

High school special programs and a college freshman engineering design seminar at the Massachusetts Institute of Technology presented an opportunity to examine how structured peer review supplements a fundamental design process: The Saturday Engineering Enrichment and Development Academy (SEED Academy) is an MIT special program that introduces high school students from Boston, Cambridge, and Lawrence, Massachusetts to engineering principles. Classes are held for ten Saturdays each semester of the MIT academic year. The SEED Academy was formed to better prepare and recruit Boston area students for the Minority Introduction to Engineering and Science Program (MITES), another MIT special program that presents a curriculum comparable to freshman year at MIT to exceptional high school rising seniors from the United States and Puerto Rico. The Second Summer Program (MIT course 2.97<sup>1</sup>) is a design workshop for MIT freshmen taught during the Independent Activities Period (IAP), which occurs during the month of January at MIT. Over many years, students in the SEED Academy (three years), MITES (four years), and the Second Summer Program (ten years) were taught Deterministic Design (DD) with a Peer-Review Evaluation Process (PREP) and used it to complete engineering projects in teams of 3–5 students. The intent was to determine what effect DD with PREP has on each stage of development and the overall development of student team projects.

## 2 Background

Deterministic Design is a process that seeks to minimize unknowns, and to map out a solution path and implementation plan. It has its origins in precision engineering [1,2] and axiomatics [3], but it uses a more relaxed format that encourages designers to feel free to think hair-raising unstructured thoughts, which preserves the fun of design. However, it insists that eventually the designer gets around to covering essential issues needed to describe, develop and realize a successful design. DD asks the designer to complete the following tasks when developing a design:

- (1) Identifying the problem and breaking it into a list of required functions;
- (2) Determining a parameter to meet each function;
- (3) Conducting analysis to gauge the effectiveness of the selected parameter;
- (4) Researching references/similar developments and comparing to analysis of selected parameter;
- (5) Conducting risk analysis;
- (6) Planning countermeasures to negate the risks.

Collectively, we suggest presenting this type of information in a FRDPARR table (Functional Requirements, Design Parameters, Analysis, References, Risks, Countermeasures). Each stage of development occurs in three phases that make up PREP (Fig. 1):

- (1) Individual thought;
- (2) Peer review (without discussion);
- (3) Discussion (brainstorming) and selection.

The overall process is similar to the Rohrbach method [4], but during the individual thought phase individuals are required to not only think wild and free, but to address essential issues (as noted above). Individuals independently develop ideas for the stage of development, and team members gather around a table and pass

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<sup>1</sup>The course syllabus and supporting information is available from <http://ocw.mit.edu>

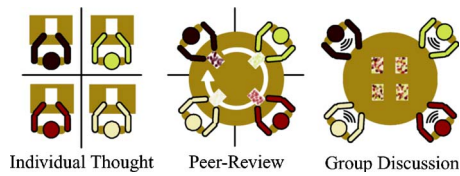


Fig. 1 Peer-Review Evaluation Process (PREP)

their ideas to their neighbor to be silently reviewed. The process continues until each individual has his or her work reviewed by every other team member, and then team members discuss the ideas they have reviewed to synthesize ideas into the “best” idea. During discussion, weighted selection occurs to determine the top idea, while also identifying strong points from all ideas and how the most favorable characteristics can be incorporated in the top idea [5]. Weighting is decided based on factors such as objectives, customer requirements, and interests of stakeholders. PREP is thus especially useful for diverse teams of designers with members from various cultures, races, genders, physical disabilities, and personalities because it first empowers people to contribute without fear of confrontation that often occurs in group brainstorming sessions. Furthermore, it provides a written record of who first came up with a concept, which can be valuable for assessing promotions or for inventorship.

Idea development is also taught to happen in a sequence of three stages from coarse to fine: Strategies, Concepts, and Modules. At each step of creation (strategy, concept, and modules) deterministic design is used. With PREP, individual design team members create (and write down their ideas), peer-review the ideas of teammates, and then discuss and select an idea as a team. It is with this crucial process, we have found in ten years of teaching that under-represented and shy people are virtually guaranteed to become fully contributing members of a design team. In addition, we have also observed that extroverted team members are happy to bring forth a great idea from a shy team member if the latter does not bring it up during brainstorming. All win in this situation.

The DD with PREP process is repeated for each of the three stages. Individual Thought, the first phase of PREP, constitutes the first action of 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, similar to the Rohrbach method. Group discussion and selection is the third phase, which helps teams solve personal creativity deadlocks and helps to ensure nothing has been overlooked as the team progresses to the next stage. PREP maintains the creativity of individuals and the power of teams, and provides a written record of how ideas evolve.

PREP reduces time to design by getting everyone fully involved, and is a framework for understanding what team members are thinking [6].

### 3 Methods

All courses involved in this study used DD with PREP, though the course objectives varied.

In the SEED Academy, high school freshmen and sophomores were introduced to mechanical and civil engineering, respectively, and used Deterministic Design in teams of four students to develop remote control cars and bridges. Cars were designed for speed, power, or a balance of the two. Bridge design types were beam, arch, and suspension. Students were introduced to mechanical engineering during the spring semester of their freshman year, a semester before being introduced to civil engineering during the fall semester of their sophomore year. This was conducted for three years three semesters of mechanical engineering, and three semesters of civil engineering.

In MITES, high school rising seniors were given a design challenge similar to sophomore mechanical engineering students at MIT in Design and Manufacturing I (MIT course 2.007). Each student in 2.007 is given the task of designing a machine to compete on an obstacle course against machines designed by fellow classmates. Individuals in select lab sections develop machines using Deterministic Design and their ideas are peer-reviewed by labmates throughout development. MITES students also develop machines to compete on an obstacle course, though they, work in teams of 3–5 students and complete their projects in five weeks as opposed to a semester. This was conducted for four summers.

For each of the last ten years, in the Second Summer Program, MIT freshmen were tasked with designing and developing products that ranged from games and toys to office supplies to learning tools and so on. Students worked in teams of 3–5 students using Deterministic Design with PREP for 20 hours a week for three weeks during the January Independent Activities Period (IAP) at MIT.

### 4 Results

The ability of students to use Deterministic Design improved with education level, but the benefit of using PREP was consistent throughout. In the ninth grade SEED Academy mechanical engineering course, students generally had trouble following the Deterministic Design process. The math proficiency of the majority of these students was well below acceptable for their grade level and for most, if not all, it was their first experience with a formal design project. It was also their first experience with reviewing the work of peers. Throughout the course, the process used by students was more trial and error guided by a design process than Deterministic Design, but students generally were able to grasp the concept of identifying risks and trying to think of possible countermeasures. However, they completed the work using the three phases of PREP, Individual Thought, Written Peer-Review, and Group Discussion and Selection. Although they had difficulty properly following the ordered process of Deterministic Design (i.e., they were working on reviewing and discussing different parts of development simultaneously) nevertheless, using PREP added the team’s input to the overall development.

With tenth graders interested in civil engineering, the students had been introduced to a formal design process, though overall their math proficiency remained below acceptable for their grade level. Still, they were able to develop bridges using Deterministic Design and their experience with PREP allowed less knowledgeable students to learn from peers. Oftentimes, students would learn things through PREP that they did not know how to do, or were too embarrassed to ask. The input they received on their individual contributions to the team project helped them become better contributors and less assistance was required from staff than in the ninth grade mechanical engineering focused course. Other factors that could have contributed to the improvements seen from ninth to tenth grade included informed selection process of students for the program, Preliminary Scholastic Aptitude Test (PSAT) preparation exercises, and gained experience of instructors. However, yearly math diagnostic exams indicate that the math proficiency of students admitted to the program had not improved and PSAT-specific preparation exercises were only recently introduced (students were always given assignments targeting areas that needed improvement discovered by way of the math diagnostic exam).

The rising high school seniors in the MITES program generally had very little trouble following the Deterministic Design process. Several had experience working in teams and some had completed recreational and/or competitive design projects. The math and science proficiency of students in the MITES program was well above the national average. Students in the MITES program were strong independent workers, but their scholastic aptitude did not always lead individuals to developing great ideas. However, the teams that were persistent in their use of PREP saw steady in-

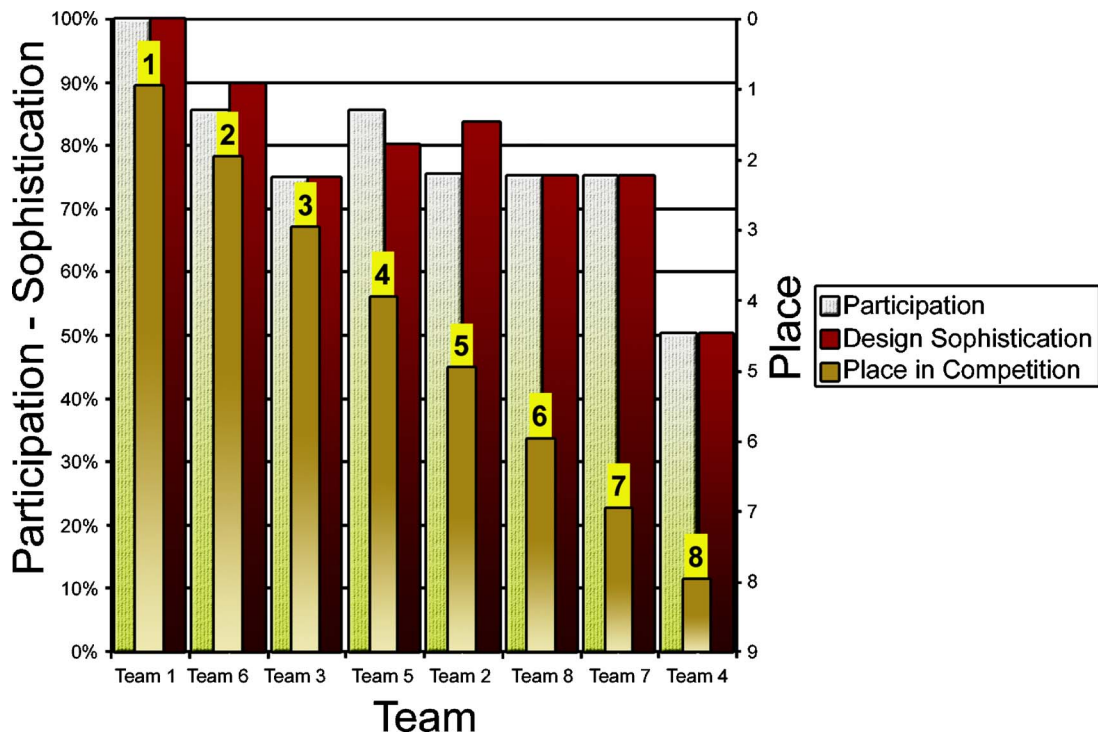


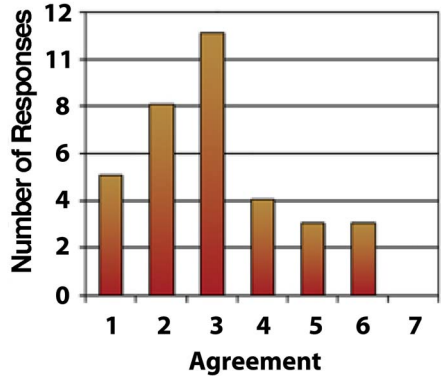
Fig. 2 MITES 2005 engineering design performance

creases in the novelty and sophistication of their designs, which directly correlated with their performance in the final design competition with their classmates (see Fig. 2). Team participation was determined by questionnaires and interviews with students upon completion of the course and direct observation by the course instructors throughout the course; use of PREP and hours spent working together in lab were the metrics considered. Design sophistication was measured by the correct use of machine elements and the overall craftsmanship of machines. Place in the competition was self-determining year after year, as performance results were based on scoring from each round. The teams with the most collaboration developed the most sophisticated designs and placed highest in the final competitions. Conversely, the teams with the least collaboration developed the least sophisticated designs and placed lowest in the competitions. Teams that placed between first and last had comparable collaboration and design sophistication. Their place in the competition was determined more by the amount of time they spent practicing operation of their machine before the competition, which was a factor for the first and last place teams as well. The first place team finished their design and manufacturing earliest and had considerable time to test and modify their machine. The team that placed last in the competition had less time for testing and modifications than any other team. Prior design experience is a factor that may have contributed to the performance of teams, though teams were selected randomly to avoid bias.

MIT freshmen in the Second Summer Program learn Deterministic Design with PREP in one lecture and use it to design and develop prototypes that satisfy a designated design objective. The students in the Second Summer Program generally are exceptional independent workers and have experience working in teams. However, when asked, many of these students describe their past teamwork experiences as situations in which their contribution to project completion greatly outweighed the contributions of their teammates; this assessment is unsubstantiated. Students in the program are proficient to very proficient in math and science, but the overall proficiency is more or less the MIT average. Teams are randomly selected and begin working on their project immediately

after being introduced to Deterministic Design with PREP on the first day of class. The Second Summer Program has a ten year history of students working in teams to complete projects using Deterministic Design with PREP. Students from 2001 to 2006 completed 14-question questionnaires regarding their use of Deterministic Design with PREP. The questionnaires covered topics from time spent working independently and with teammates in and out of the machine shop to how use of the process improved independent and group work habits and performance. Each year, upon completion of the Second Summer Program, most to all of the students (depending on what is available) are offered summer internships with sponsoring companies. The companies express their contentment with the performance of the students through continued support for the program and rehires of the students for return internships and offers after graduation. The Second Summer Program was founded with the purpose of preparing students for summer internships. We have found completing projects using Deterministic Design with PREP to be an effective method for preparing Second Summer Program students for summer internships and improving their scholastic performance in general (see Figs. 3 and 4). Out of 34 survey respondents from 2001–2006, over 65% agreed the Second Summer Program prepared them for summer internships and improved their performance as students. We believe we saw these results because Deterministic Design not only provides a framework for creative development, but work and development in general. In addition PREP is a decidedly constructive approach to working with others and improves communication skills. Peer-review is conducted without talking, so students become effective at written communication. Students also become effective at reading the work of others and providing constructive criticism. In addition, Group discussion helps students become comfortable with oral communication. In fact, students surveyed reported a 93.9% average comfort rating with presenting their ideas to the rest of the team and an 86.7% average agreement that their ideas were recognized by the rest of team (see Figs. 5 and 6). However, perhaps the greatest testament to the satisfaction of students with Deterministic Design with PREP is how often those who learned the process continue to use the ap-

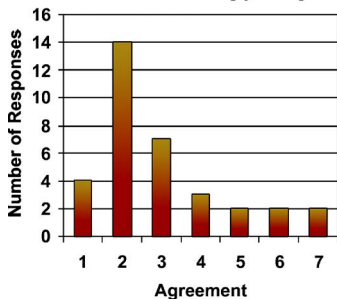
**Agreement Second Summer Program Experience Prepared for Summer Internship: 1 Strongly Agree to 7 Strongly Disagree**



**Fig. 3 Questionnaire results from six-year Second Summer Program study—preparation for summer internship. Agreement Second Summer Program experience prepared for summer internship: 1-Strongly Agree to 7-Strongly Disagree.**

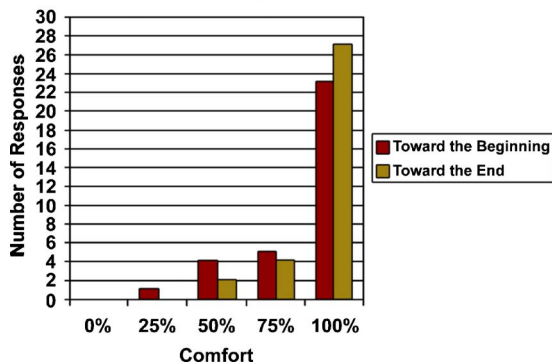
proach in their work with others (see Fig. 7). In their current work with others, over 45% of former students use PREP 75% of the time and over 75% of them use PREP at least 50% of the time. A factor that likely influenced the rapid adaptation of Second Summer Program students to the use of Deterministic Design with PREP is the instructor (teacher and teaching assistants) to student

**Agreement Second Summer Program Helped Become A Better Student: 1 Strongly Agree to 7 Strongly Disagree**



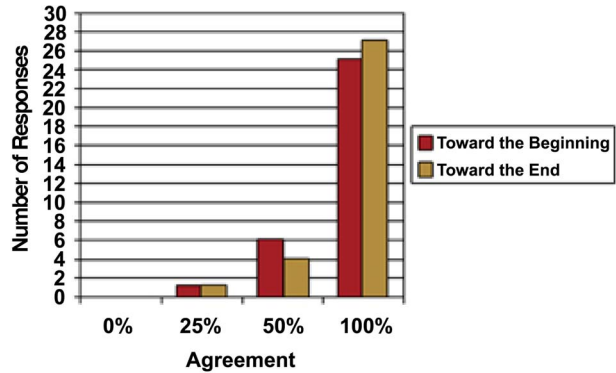
**Fig. 4 Questionnaire results from six-year Second Summer Program study—improvement as a student. Agreement Second Summer Program helped become a better student: 1-Strongly Agree to 7-Strongly Disagree.**

**Comfort Presenting Ideas to Rest of Team**



**Fig. 5 Questionnaire results from six-year Second Summer Program study—comfort presenting to team**

**Agreement Contributions Were Recognized by Teammates**



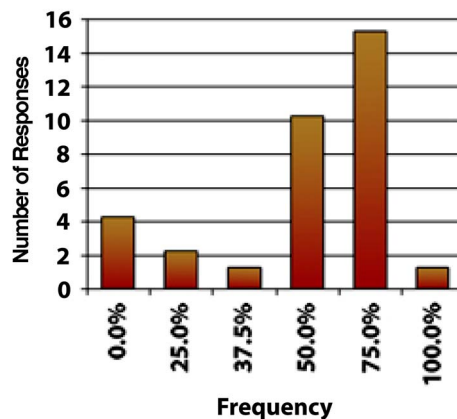
**Fig. 6 Questionnaire results from six-year Second Summer Program study—contributions recognized by teammates**

ratio, which was significantly greater than those of SEED Academy and MITES. SEED Academy typically had a 1:12 instructor to teacher ratio. MITES typically had a 1:7 instructor to student ratio. The instructor to student ratio for the Second Summer Program ranged from 1:4 to 1:2.

### 5 Conclusions

In the past ten years, over 400 students in MIT special programs learned Deterministic Design with PREP. Students who learned the process ranged from high school to college freshmen. We saw a major difference in students' ability to apply Deterministic Design with respect to their educational background. Students with weak math and project work backgrounds initially had trouble with Deterministic Design. Students with strong math, science, and/or project work backgrounds were quick to adapt to the use of Deterministic Design. We found that students' ability to conduct PREP was not hindered by a depressed educational background. Furthermore, PREP improved individual contributions to

**Since Completion of the Second Summer Program When Working With Others How Often Phases of PREP Are Applied (1. Individual Thought, 2. Written Peer-Review, and 3. Group Discussion)**



**Fig. 7 Questionnaire results from six-year Second Summer Program study—since completion of the Second Summer Program when working with others, how often phases of PREP are applied (1 Individual Thought, 2. Written Peer-Review, and 3. Group Discussion)**

**Table 1 Summary of classes taught using Deterministic Design with PREP**

| Variables   | SEED                            | MITES                      | SSP                   |
|---|---------------------------------|----------------------------|-----------------------|
| Educational level                                       | High School Freshmen–Sophomores | High School Rising Seniors | University Freshmen   |
| Student educational background                          | Below Average–Average           | Average–Above Average      | Average–Above Average |
| Student scholastic aptitude                             | Below Average–Above Average     | Average                    | Average               |
| Student design experience                               | None–Moderate                   | None–Moderate              | None–Moderate         |
| Instructor to student ratio                             | 1:12                            | 1:7                        | 1:4–1:2               |
| Instructor experience in Deterministic Design with PREP | Experienced                     | Experienced                | Experienced           |

the team and in turn the overall team performance. If completing PREP with Deterministic Design is much better than Deterministic Design without PREP, groups that do not use PREP would be receiving less of an educational benefit, therefore, we instructed all teams to complete their projects using Deterministic Design with PREP. While control groups without PREP were not run, through weekly reviews, teams that were not using PREP were identified and this non-performance was reported. Deterministic Design dictated the milestones, though Deterministic Design and PREP were the deliverables. Teams would meet the Deterministic Design milestone, but some teams would not use PREP; these teams invariably did worse than teams that used PREP, as is shown in Fig. 2: MITES 2005 Engineering Design Performance. The top team was consistent with PREP, had the best design, and placed first in the competition. The bottom team was inconsistent with PREP, had the worst design, and placed last in the competition. The results were the same each year. Designs of teams that used PREP were consistently better designed and better built than

those of teams that did not use PREP. In competitions, design teams that completed projects using Deterministic Design with PREP largely outperformed teams that used Deterministic Design without PREP. Factors that may contribute to easy adoption of Deterministic Design with PREP include experienced instructors, prior design experience of students, and high instructor to student ratios [7]. Hence, Table 1 suggests that SEED Academy students may be at a disadvantage to MITES and Second Summer Program students in the adoption of Deterministic Design with PREP. The SEED Academy students did have trouble adopting Deterministic Design. However, in each program teams that used Deterministic Design with PREP outperformed teams using Deterministic Design without PREP, which supports the conclusion that PREP enhances team collaboration and performance.

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