Work in Progress: Oh ... The Irony (A Six-Section Rube Goldberg Machine for Freshman Engineering Design)

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Abstract

This Work-In-Progress paper discusses the experience within a freshman engineering design course in which students are asked to conceive, design, implement and operate a ***Six-Section*** Rube Goldberg machine. Often in the first year of an engineering curriculum there is a project based class designed to introduce students to, motivate students about, and retain students within the engineering discipline. They also begin to instill skills such as:

1. Team Work
2. Systems Engineering through Experimentation, Testing, and CAD & physical Modeling
3. Written Communication
4. Oral Communication
5. Time Management
6. Team Management

At this institution, project based classes allow students to develop these skills and expressly enforces two avenues of technical communication: ***between and among*** groups. Constant communication, between and among groups, is included to simulate a workplace environment where workers are not limited to their singular work groups, but to share their designs, knowledge, and ideas with the other participating groups within a project. This is accomplished by asking a class to conceive, design, implement, and operate (CDIO) a ***Six-Section*** Rube Goldberg machine (a system with many complicated steps to accomplish a simple task – an inefficient design). Each of the groups (~4 students per group) are required to conceive, design, implement and operate ***their own*** 15 step Rube Goldberg section with a final task of all 6 sections working as a homogeneous machine.

In previous implementations of the course, the CDIO process was used, however projects rotated between teams at the end of each project phase. While enforcing technical communication between teams, it came at the cost of overall class atmosphere and group/project success. The CDIO class design allows for prescribed opportunities for technical communication though written reports and oral presentations, but rotating the teams also allowed the students to divest themselves from the project at the end of each phase. Combining the CDIO process with a new project was necessary. Connecting six Rube Goldberg Machines allows for individual success of a team's own project and still asks teams to communicate to ensure success for the whole class as all six sections come together to create the ***Six-Sections*** Rube Goldberg machine.

This paper discusses the results of a carefully crafted project in a freshman engineering design course that maintains multiple avenues of technical communication (between and among groups) through reports, presentations, and technical graphics. It also provides students opportunities to learn time and team management. Finally, the project requires students to proceed through a rigorous design process while allowing for creativity within the design. The irony of the fact that typically Rube Goldberg Machines are designed to do a simple task through an *inefficient* process is well understood and accepted; engineers *should* search for *efficient* designs and solutions to problems. Overall, the project was warmly received. We will also touch on plans to assess the impact of freshman design course and the student end-of-semester comments with longitudinal studies.

Introduction

This Work-In-Progress paper describes the current standing and implementations of a project based freshman design class that enforces technical communication and teamwork. This project based class is taught in the first year of an engineering curriculum to introduce students to, motivate students about, and retain students within the engineering discipline[1]. The program measures three ABET Student Outcomes in this course: Outcome C (design a system, component or process), Outcome D (teamwork and function on multi-disciplinary teams), and Outcome G (communicate effectively). This program assesses these outcomes in a student's first year (Systems Engineering and Freshman Design) and senior level (Senior Capstone). As a work in progress, the goal of this curriculum is to give first year engineering students the ability to recognize and experience the importance of Outcomes C, D, and G. In addition, the program aims to improve these skills throughout a student's schooling, into their Senior Capstone, and beyond. This institution has made several changes to their Systems Engineering and Freshman Design course that focus on these three outcomes and as students reach graduation, they are reevaluated to assess the effects that their freshman design course has on their practices used in their Senior Capstone.

The Conceive-Design-Implement-Operate (CDIO) framework for project execution was first introduced in 2012 at this institution and provided a good framework for students to design a system, component or process; Outcome C[2,3,4,5,6]. The course split into 4 phases – 3 weeks in Conceive, 4 weeks in Design, 6 weeks in Implement, and 2 weeks in Operate. Through this framework, students are provided a problem statement and use this framework to determine the best solution. However, improvements to the course were necessary to address Outcomes D and G. In 2015, Outcome D was addressed by investigating team formation. Using different grouping strategies, team performance was assessed. Results show that students grouped with an array of GPAs (high, middle, and low incoming GPA) performed better than those groups that were completely randomized or grouped with similar GPA[3]. Finally, in 2016, a new project was introduced to improve communication between and amongst teams: Outcome G. From 2012-2015, a strategy of rotating projects between each design phase was used. This was intended to illustrate the importance of communication. However, the strategy did not achieve its goal. This paper describes the new project and initial results regarding its execution relative to Outcomes C, D, and G and plans to assess the impact of freshman design course and the student end-of-semester comments.

Course Structure

CDIO - Execution

In the 2012 reorganization of Systems Engineering and Freshman Design, already addressing Outcome C, was restructured so that a 24-person class had 4 different group projects run by six person teams. In addition, student were taught CAD and solid drawing fundamentals as part of the course curriculum. In the restructuring, each team was assigned a different project at the start of the semester. At the end of each CDIO phase, student groups delivered written reports and oral presentations regarding their progression through each phase. The class proceeded into the next phase with a new group taking over from where the previous team ended. This structure will be referred to as “Rotating Teams”. This was intended to address Outcome G by having oral and written communication rotated between groups. For example, one year the four projects that teams were required to CDIO were:

1. Lighter-Than-Air-Vehicle (LTAV) that can navigate over and under a basketball court’s two rims
2. Balsa Wood Building (BBEQ) that could withstand a specified ground excitation or earthquake
3. Water Vehicle (WVSP) that could be used to clean an artificial oil-spill (ping-pong balls)
4. Wind Powered Land Yacht (WPLY) that could navigate the baseline of a basketball court using two industrial sized fans

Team A began the semester in the Conceive phase with the LTAV project, but continued into the Design phase with the BBEQ project, Implement the WVSP project, and finally Operate the WPLY project. This modeled real world scenarios, in which engineers may not see their whole project all the way from conception through operation.

Although some students understood the reason for Rotating Teams, they did not always appreciate the results of a previous team’s work, nor were all the projects successful by the end of the semester. Often times, student teams would begin each phase from scratch, completely rebuilding and/or redesigning the previous groups entire project. Students comments ranged from “I didn’t like their design,” to “their design didn’t work,” to “I just thought it would be easier to do this my way.” The students were more concerned with having a successful/operational product at the end of each phase and class. If they were not concerned about the success of the project, they would conveniently blame their non-success of the previous phases’ failure to produce good results.

Upon these observations, this institute decided to retain the CDIO process and implement a new project that still emphasizes technical communication and teamwork while fulfilling the design requirements of the course.

Rube Goldberg Re-vamp

In an effort to address the problems observed between 2012 and 2015: large rotating groups; student teams scrapping previous work; and (selfishly) starting the whole project from scratch and implementing “their-own” ideas, the instructors:

1. developed a new project statement using a Rube Goldberg Machine
2. configured the teams differently in both size and makeup
3. removed all CAD and Solid Drawing lessons and transferred its content to a new course.

Rube Goldberg Machines have been used in many different forms in different classes to motivate students regarding engineering.[6,7,8,9,10,11,12] Graduating from University of California – Berkley with an engineering degree, Rube Goldberg gained fame for his illustrations of complicated gadgets that performed seemingly simple tasks. These cartoons led to the term Rube Goldberg Machine: "any **very complicated** invention, machine, scheme, etc. laboriously contrived to perform a seemingly **simple** operation."[13] There-in lies the irony – during a project, engineers should never design a complicated machine to accomplish a simple task. However, this is a chance to let our students put their creativity, and excitement about engineering, to good use.

To affect Outcome D, groups of four were arranged by GPA, according to Chlebowski et al.'s findings[3], and asked to CDIO a Rube Goldberg Machine. In addition, the groups maintained their project throughout the entirety of the course. This structure will be referred to as Non-Rotating Teams. Technical communication (Outcome G) focused on team-to-team interaction throughout the design process to connect all six individual Rube Goldberg sections into one Six-Section Rube Goldberg Machine – where the end of one section activates the next.

In the Systems Engineering and Freshman Design course, the Six-Section Rube Goldberg Machine's ultimate task was to raise a school pennant. The main requirements (All requirements seen in Appendix 1) are:

- There must be a minimum of 15 steps within each **section** of the Rube Goldberg Machine
- Each section of the Rube Goldberg Machine must have a theme.
- **No duplicate steps** may exist within the whole Rube Goldberg Machine
  - Steps after similar events must be unique
  - At least 1 step must include a problem statement and solution related to a "Kinematic Problem" *(this means you may need to learn something new!)*
  - At least 1 step must include a problem statement and solution related to a "Dynamic Problem" *(this means you may need to learn something new!)*
  - Each step must be explained, correctly using the appropriate engineering terminology such as *(this means you may need to do some research!)*
- You MUST include Lego NXTs in your design
- Design/Create a 3D-Printed part that must be designed and incorporated into each section of the Rube Goldberg machine
- You are supplied a minimal starting set of materials. No additional material will be provided during the semester. However, you may add your own parts to your machine.
- One member of each team must be designated **Liaison (or Team Captain)** for each phase of the project.

Discussion

The project was success, and each Rube Goldberg machine was achieved its goal. Comments from students included:

- I felt that the project was an excellent idea. It was an adventure mentally and physically. Many new skills were learned as well as existing ones being strengthened. It was challenging and rewarding.
- The lab was a great learning experience … but … "it required a lot of work"
- The lab was fun but the project should be reduced to 10 steps
- The instructor did a good job. This was a fun project. I would recommend doing it again.
- I really enjoyed this class; however, I did not like the group I was with. We should be able to pick our groups.
- I enjoyed the lab and felt I had ample time to complete what was asked of me. I wish I had more supplied to work with.
- Very fun, enjoyable project. The instructor does a great job.
- The instructor did a good job. This was a fun project and it is one to remember. I would recommend doing it again.
- Overall enjoyed the class. Some material was bust work. Too much for a 2 credit hour class

Students were so invested in their projects that they took to posting dry-run and demonstration videos to YouTube. This shows that students clearly took ownership of their Rube Goldberg Sections. A second indication is the improvement in grades leading to the end of the course (Table 1).

With the Non-Rotating Teams course, grades increased from the Implement to the Operate phase, illustrating that the students wanted to see their Rube Goldberg Machine all the way to completion. Percent difference between Conceive to Design phase report grades are not indicated in Table 1. Assessment of this metric is not considered because this course is a student's introduction to technical communication. Students are provided detailed formats of report and presentation requirements. However, their conceive phase report grades were rather poor. In an effort to motivate students to improve performance, this grade is usually overwritten by the design phase grade. Instructor feedback after the conceive phase sets a precedence for the expectations for written and oral communication.

The Rotating Teams course generally has a negative trend in report grades between phases, indicating that the students' grades decreased; they lost interest in creating accurate documentation and quality reports. This is the portion of the course where students feel pressured to make the project successful. The expectations are that students will reference a previous team's work, but this rarely occurred.

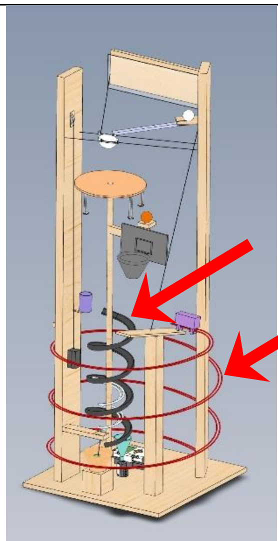
Table 1: Percent Difference in Between Phase Report Grades for two different classes (Same Instructor)

	Rotating Teams (Spring 2015)		Non-Rotating Teams (Spring 2016)	
Section	Design to Implement	Implement to Operate	Design to Implement	Implement to Operate
1	-2.94%	-12.94%	-3.25%	4.71%
2	6.88%	-2.36%	-5.33%	7.05%

These results hint that the changes in the course structure and project positively affects student performance. This could be attributed to several factors, not limited to: team grouping strategy[3]; the size of the teams; and students maintaining ownership of the project.

Another indication of their investment is that students also took it upon themselves to learn new CAD/Solid Modeling skills that were not taught in the new CAD/SolidWorks course. Examples include unconventional angles, arcs and spirals (Figure 1). This Rube Goldberg project challenged and inspired students to reach beyond the requirements of the course visualization (graphic) and technical communication goals.

At the end of the semester, students were asked to provide insight (or helpful hints) to future students enrolled in the course. They left notes on the classroom dry erase board. Comments tended to fall into four categories: 1) planning & time management, 2) the design process, 3) teamwork and 4) communication (Table 2). As expected, there were several comments regarding procrastination. Notice there are many comments regarding testing. In an effort to make their Rube Goldberg section operational, students gained an appreciation for the efforts necessary to test their designs and document their results. Comments regarding communication hit on the aspect communication between teams and their written communication in their reports. And of course, there were remarks regarding teamwork; please notice that there are comments regarding communication within each team – an important aspect of teamwork. Finally, there was one comment in particular that illustrated the need for better communication as to the roles of students in the group.



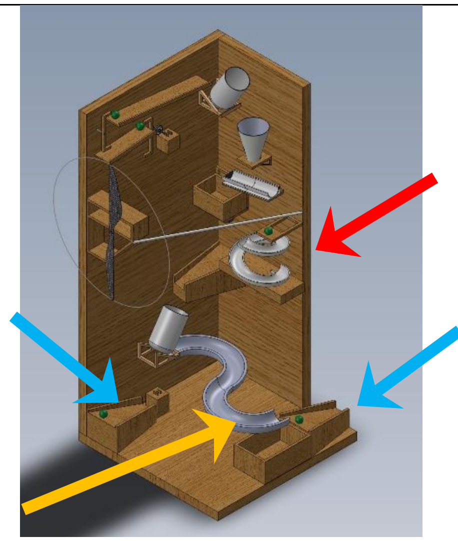


Figure 1: Example of SolidWorks Designs
Examples of use of unconventional angles are indicated with Blue Arrows. An example of use of an Arc is indicated with an Orange Arrow. Use of spirals are indicated with Red Arrows.

Table 2: Student End of Semester Feedback (Tips to future classes)

Planning & Time Management • Start early/ Don't Procrastinate • Start building early so your aren't rushed at the end • Actually bring your materials to class • Plan/Work ahead	**Communication** • Communicate with other teams • Be specific in reports (Mentioned 3 times)
The Design Process • Test, test, test, document, document, document • Don't redesign unnecessarily • Test early and often • Choose a story that works well with steps (transfer of energy) • Testing! Testing! Testing! • If possible, make each step operate at 200% efficiency – Assuming you are building a manned space ship, you can't take risk – be safe.	**Teamwork** • Team work • Be creative and split up work • Keep in contact with your team! • Split up Tasks, for reports early! • Be positive • Listen to all ideas from all sources! • A liaison does not make a leader. Don't assume the liaison in the leader of the team, and instead assign roles early in the semester and stick with them. Having one leader throughout the semester makes for a consistent direction for the whole project.

With respect to ABET Student Outcomes, clearly from the comments in Table 2, students have at least been made aware of the importance of Outcomes D (function on multidisciplinary teams) and G (communicate effectively). In addition, the students were successful in completing their designs for each Section of their Rube Goldberg Machine (Outcome C). As part of this work-in-progress, feedback will be obtained regarding Outcomes C, D, and G from these students during their Senior Capstone. Students will be asked to reflect on their comments and if they were used in the execution of their Senior Capstone. Students will also be assessed on the impact their freshman design course had on their ability to design a system, component or process, to function on a multidisciplinary team, and to communicate effectively.

Conclusions

It is suspected that there is a positive impact on student learning using the techniques described. Students were successful in their projects. They took ownership of their individual Rube Goldberg sections. There were NO complaints regarding transitioning through phases with another team's shoddy work – all work was their own. They also realized the importance of inter- and intra-team communication as it speaks to the success of the whole project.

There were several instances in which student comments illustrated that they have learned aspects of engineering and communication. Hopefully, these students will carry these insights forward into their future years at this institution (or any other); lessons on Planning and Time Management, Design, Communication, and Teamwork. Assessment of these freshman students will occur in their Senior Capstone to view a longitudinal trend with respect to the program assessment of the same three ABET Outcomes (C, D, and G.)

The irony of all of this is that students were asked to design a Rube Goldberg machine that conducts 90+ steps to complete a simple task. The insights they found through the use of the Rube Goldberg machine will hopefully be a starting point for students to hone their design, communication, and teamwork skills such that they can design, communicate, and work on teams effectively in their Senior Capstone and beyond.

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APPENDIX 1 Rube Goldberg Problem Statement

Your task as a class is to:
Conceive, Design, Implement and Operate a Rube Goldberg Machine that raises the base of a mini-USI flag a total distance of 5 feet. The base of the flag must start from the machine base.

- Each team (4 Students) must Conceive, Design, Implement and Operate **1 section** of a Rube Goldberg Machine.
    - No part of a team's machine or any associated materials may be attached in any way to the walls, floor, or ceiling of the venue. No action of building, cutting, or drilling shall damage furniture provided at the venue.
- One member of each team must be designated **Liaison (or Team Captain)** for each phase of the project.
    - There must be a different Liaison for each consecutive phase
    - Everyone person in the team must be a liaison at least once!
    - The Liaison
        - is responsible for setting meeting agendas and assigning tasks to team members
        - is responsible for interacting with other liaisons during each phase of the project
        - will **lead** (not responsible for WHOLE presentation) their team's presentation of the machine during each phase to the judges, including an explanation of the process of creating the machine, a detailed description of how the machine works (including each step of the process), and the outcome.
- There must be a minimum of 15 steps within each **section** of the Rube Goldberg Machine
    - A step is defined as an event that transfers energy from one component of the machine to another component.
    - Starting events does not count as 1 step
- Each section of the Rube Goldberg Machine must have a theme.
    - Each event in the section of the Rube Goldberg machine must be related to this theme.
- **No duplicate steps** may exist within the whole Rube Goldberg Machine
    - Steps after similar events must be unique
    - Similarity of steps will be judged (by Dr. Davis) and must be defended (by Liaison) to be unique.
    - At least 1 step must include a problem statement and solution related to a "Kinematic Problem" <u>*(this means you may need to learn something new!)*</u>
        - You must show theoretical solution
        - You must show repeatable experimental solution
        - You must show data analysis of experimental solution
    - At least 1 step must include a problem statement and solution related to a "Dynamic Problem" <u>*(this means you may need to learn something new!)*</u>
        - You must show theoretical solution
        - You must show repeatable experimental solution

        - You must show data analysis of experimental solution

    - Each step must be explained, correctly using the appropriate engineering terminology such as *<u>(this means you may need to do some research!)</u>*
        - Potential Energy
        - Kinetic Energy
        - Linear Momentum
        - Angular Momentum
        - Force
        - Acceleration
        - Velocity
        - Position

- You MUST include Lego NXTs in your design
    - You will be allowed to incorporate 2 NXT Motors into your design
    - Lego NXTs must be programmed using Matlab or Simulink (NOT Lego NXT)
    - You must/will be able to set up (and break down) in less than 7 minutes

- List of standard materials (will not be replaced)
    - 0.25” by 0.25” Balsawood (16 pieces)
    - 0.125” by 0.125” Balsawood (8 pieces)
    - Wood Glue (as necessary)
    - 1 big wood ball (per class)
    - 1 small wooden ball (per team)
    - 6 wooden Popsicle sticks
    - 1 spring
    - 2 magnets
    - 3 rubber bands
- **$ 45 of material (Fortus vs. Polyjet)** from 3D Printed pieces must be designed and incorporated into each section of the Rube Goldberg machine
    - The pieces must be printed during the first week of the implementation phase (see professor for dimension limits and printing procedure)
    - The pieces must be used in and/or with your Rube Goldberg section during operation.
    - Please contact Dr. Chlebowski for pricing and printing
- You may manipulate the base plate, but it must provide structure to your machine.
- Your team must be able to lift and move your section into place.
- Your section must fit within a confined volume of 1.5 × 1.5 × 5 feet.
- You are supplied a minimal starting set of materials. No additional material will be provided during the semester. However, you may add your own parts to your machine. These parts
    - MUST BE CLEAN!
    - MAY NOT HAVE SHARP EDGES!
    - MUST BE APPROVED BY Dr. Davis before incorporated into your machine

- Must be accounted for at every stage in the process of design, implementation and operation. So, please keep record of:
  - Piece
  - Intended Use
  - Date of Approval
  - Cost