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A Pilot Program in Opem-Ended Problem Solving and Project Management

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Abstract

This research is motivated by the need for students' early exposure to work readiness skills that promote effectiveness in dealing with complex open-ended technical problems as may be encountered in senior capstone projects or professional practice. This paper presents preliminary work in the building of Rube Goldberg machines as student projects to foster some of these skills. Design of Rube Goldberg machines may be employed in a number of settings as a vehicle for teaching basic engineering skills. These designs require students to creatively consider a variety of unconventional approaches to solve simple problems. The Rube Goldberg paradigm allows students to communicate and to advance their ideas in a low-pressure environment where brainstorming is highly valued and where prior technical expertise affords no specific advantage. As such, projects based on Rube Goldberg machines are an effective way for freshmen and sophomore students, who may lack extensive technical skills, to acquire greater proficiency in some of the non-technical skills. This research gives results from a pilot study that uses the Rube Goldberg model to enhance some work readiness skills. The goal of this study is to determine the perceived efficacy of a proposed teaching vehicle for project management concepts that could strengthen the early stages of an existing series of Project Based Learning (PBL) oriented undergraduate engineering courses at the host institution, which currently make use of more closed-ended and single-solution design projects. In the study, a cohort of 27 engineering and engineering technology students participated in a sequence of extracurricular sessions in which they undertook progressively challenging open-ended project assignments. Each project introduced new constraints that required the students to address additional aspects of project management. Results from an end-of-year survey show that the participants had strongly positive impressions of their experiences related to these exercises. A majority of students felt that they had enhanced skills that would be valuable in professional life (96%), improved their leadership skills (92%), and had gained appreciation for the value of project planning (100%) and technical documentation (96%). It is anticipated that lessons learned from the project sequence will provide the framework for cross-disciplinary freshman and sophomore assignments in host institution's PBL curriculum in the future.

Keywords: Project management, Rube Goldberg machines, Project Based Learning

1. Introduction

Accreditation of engineering programs has long provided a means of *quality control* of graduates in the United States.[1] In recent years, this practice has come to reflect an emphasis on the *outcomes* of student learning rather than on restrictive earlier notions centered on what is being taught.[1,2,3] Previous thrusts in engineering education development have stressed the graduate's technical competence in engineering science, and engineering design as outcomes.[3] However, studies by industry employers have revealed that these competencies do not sufficiently equip students with skills needed for the more socially intensive aspects of modern engineering practice.[2,4] In order to be fully work ready, additional skills in less observable areas[4] need to be developed. These include social skills such as leadership,[5,6] interpersonal communication, emotional intelligence, and an ability to work in diverse groups, as well as skills in problem solving, awareness of sustainability, and engineering ethics.[5]

Project Based Learning (PBL) is a vehicle for *inductive* learning[7] in which a (poorly defined) task to be accomplished necessitates the tools that students must acquire in order to complete it. PBL has been previously applied to the development of technical and project management skills for engineering students.[8,9] In such cases where students make use of prior knowledge, implementation difficulties are mitigated for the instructor, and students are more receptive to the assignment.[7] For these reasons, projects involving Rube Goldberg machines are frequently employed[6,8,9,10] as they presume a minimal common knowledge base but no specific expertise.

The unconventional, and often humorous, nature of Rube Goldberg machines facilitates an enjoyable and motivating environment for students in the early stages of their engineering study.[8] Further, the lack of a need for extensive engineering knowledge places all members of a project team on an equal footing, which may encourage the free flow of ideas between otherwise reticent individuals. Within such a scenario, brainstorming and creativity are valued over technical expertise. The more *human* skills of communication, social interaction and integration in diverse team environments that are demanded by industry may be fostered along with technical and management skills. Students early in their degree progress who would benefit from these experiences will also carry the skills learned into their upper coursework, capstone projects, and into professional practice.

This research makes use of Rube Goldberg machine construction as the foundation of a pilot study for the development of an interdisciplinary PBL teaching method that incorporates open-ended design challenges. If successfully developed, the approach would be used to enhance the early stages of an existing five-course PBL sequence in the engineering curriculum at Western Carolina University (WCU) where this work was conducted. The PBL sequence at WCU has historically employed more closed-ended, single-solution design projects. It has been observed by the authors that, particularly in the early stages of the curriculum, emphasis on effective communication, teaming, open-ended problem solving, and an understanding of quality is of high instructional impact.

With these objectives in mind, a cohort of engineering and engineering technology students were involved in series of Rube Goldberg projects of increasing complexity. The projects were undertaken outside of normal class work during the 2015-16 academic year. At the end of that year the students completed a survey which gathered their perceptions of the experience. This paper presents a reflection on these perceptions as motivation for future work. Based on the collected impressions, it is envisioned that similar projects would be a useful component of the existing PBL curriculum (Figure 1) at WCU, particularly in introducing work readiness skills at the earliest stages.

This paper is structured as follows. Section 2 describes the method and scope of the study. Section 3 describes the student cohort of participants. Section 4 describes the project materials kit and the project sequence developed for the study. Section 5 discusses the survey taken by the students and identifies notable outcomes and their relative support for the efficacy of the approach. Section 5 discusses conclusions and possible future extension of the work.

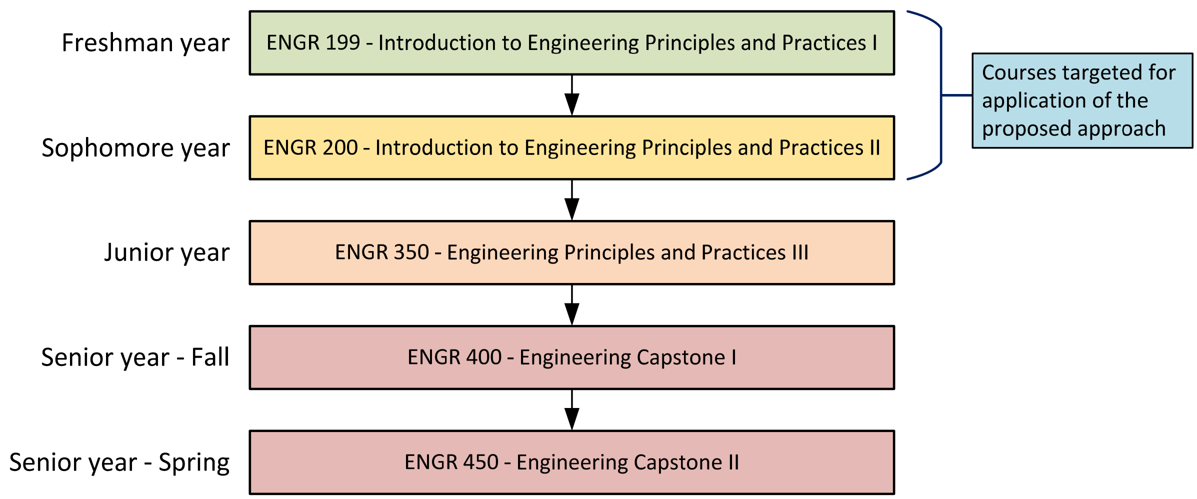

Figure 1 – The existing PBL course sequence at WCU. The proposed approach may find application in ENGR199 and ENGR200.

2. Method

This study has been primarily designed to serve as a pilot. The open-ended projects assigned to the students are expected to result in ideas that could be further investigated and incorporated into the PBL course sequence in the existing curriculum at the host institution (as indicated in Figure 1). The pilot study is conducted to incorporate design innovation, brain storming, and team work over a short span of time (typically 1 to 3 weeks per exercise) to come up with solutions for open-ended design challenges. The secondary aim of the study is to strengthen project management and team work skills among the cohort of participants. The student-driven nature of these projects is known to enhance student engagement.[11]

The study aims at determining the student response to such projects before incorporating these methods in a classroom setting, as recommended in the literature.[11] Since the students involved in this study are not graded for their performance, their frank feedback on different aspects of the projects will be critical in future adaptations of similar projects in a classroom environment. Furthermore, since the projects are not tied to a course grade, students are less likely to be inhibited by failure or reward.

An anonymous survey was conducted after completion of all the projects to assess the students' perceptions of learning and to obtain student feedback. Since the number of students involved in these projects is relatively small, statistical analysis is not expected to be useful at this stage. Therefore, data collection has been limited to self-reporting and attitudinal measures. Although it is acknowledged that self-reporting has several limitations, it is useful for this study since it serves the role of a pilot. Once fully implemented within the host institution's PBL course sequence, a more robust study could be conducted to determine the efficacy of these strategies across a much larger sample, containing approximately 200 students.

3. Student Participants

Students participating in the pilot study were members of the cohort of scholarship recipients in the SPIRIT Scholarship Program at WCU. The program[12] is funded by the National Science Foundation and is directed by the authors. The program provides assistance to academically gifted, financially needy students who are pursuing degrees in engineering or engineering technology in the host department.

The cohort consists of 27 students: 4 freshmen, 7 sophomores, 11 juniors, and 5 seniors. These students are pursuing one of the four degrees housed in the host department. Degree programs include electrical engineering (BSEE), mechanical engineering (BSE ME), electrical and computer engineering technology (BS ECET), and engineering technology (BS ET). The distribution of students by degree is given in Figure 2.

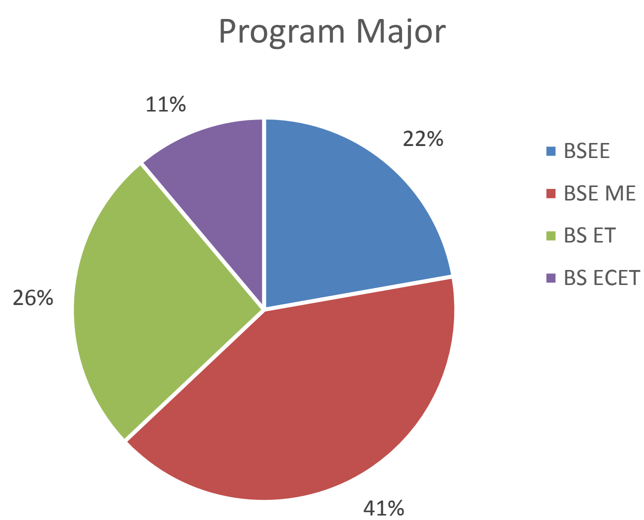

Figure 2 – Academic major selection among students in the program.

The scholars and the program directors meet once per week as a group. Meetings afford the scholars opportunities to hear guest speakers, to participate in group discussions, and to work in small group problem solving sessions such as those described in this research.

Prior to the start of the program, all program directors completed appropriate training to conduct research with human participants. A request to pursue this research was submitted by the directors and approved by the Institutional Review Board (IRB) at WCU. Participating students were required to sign an informed consent form that was also approved by the IRB.

4. Project Descriptions

Five short-duration Rube Goldberg projects were conducted for the pilot study. Projects were designed to take 1-3 one-hour weekly sessions. The program directors presented targeted learning outcomes to the cohort prior to the start of each project. Six different project teams of four to five students each were formed. Teams included at least one student from each program year (e.g., one freshman, one sophomore, etc.) and students of different academic disciplines (mechanical engineering, electrical engineering, engineering technology, and electrical and computer engineering technology) wherever possible.

Each team received a project kit containing materials to be used in construction of the projects. The kits were contained in large plastic totes (tubs) and consisted of low-cost commonly-available items which may be purchased through many general merchandise retail stores. A list of items contained in each kit is given in Table 1.

Table 1 – Project kit contents.

Item	Quantity	Item	Quantity
String	50 ft.	Aluminum foil (roll)	1
Chinese checker marbles	10	Compressed air (can)	1
Stick pins	1 pack (50)	Whisk	1
Dominos	1 box	Mouse traps	2
Tin can	2	Tongue depressors	50
Magnets: 1/4", 5/8", 3/8"	8, 2, 1	Paint stir sticks	16
Nuts and bolts (1/8")	4	Plastic cups	16
Rubber bands: 17", 14", 12", 7", smaller sizes	3, 3, 3, 3, 50	Drinking straws	10
Plastic spoons	8	Construction straws	70
Duct tape	1 roll	Straw connectors	50
Tennis balls	3	Paper towels (roll)	6
Wood screws: #6-3/4", #6-1/2", #6-5/8"	16, 16, 16	Modeling clay	1 pack
Wind-up toys	2	Slinky	1
Hot Wheels cars with track	1	Funnels	3 (various sizes)
Lead fishing weights	2	Pencils (with erasers)	10
Cork or rubber stoppers	5	Paper clips (assorted)	100
Bottled water	4	Binder clips (small, medium, large)	1, 1, 1
Kids fishing rod with reel	1	Pipe cleaners	22
Plastic tubing: 1/2"	10 ft.	Push pins (box)	1
Hot glue gun	1	Kite string	1 roll
Glue gun sticks	16	Twin	1 roll
Elmer's glue	1	Index cards	16
Epoxy	1	Pulleys	2
Velcro	1 yd.	Cardboard tubes	4
Clear tape	1 roll	Dowels: 12"	2
Springs (bag, assorted)	1	Lumber: 2" x 4" x 28"	2
Plastic drop cloths	1	Ball bearings: 1/8", 1/4", 3/16"	24, 8, 1
Plastic pail with handle	1	Bouncing balls (assortment)	8
		Plastic tote (90 qt.)	1

Initial supply cost for six project kits was $1800 total. Yearly replenishment cost has been approximately $60 over all kits, with duct tape, glue sticks, compressed air cans, and string being the most frequently consumed items.

The topic themes for the projects included teaming strategies, situational leadership, the *Keep It Simple Stupid* (KISS) engineering design concept, the importance of design documentation, concepts of quality, and project management strategies related to time and use of materials. Projects were structured to reinforce these concepts as the students encountered several preplanned project pitfalls. Each project built upon the theme and concepts of its predecessor and varied so as to address several learning concepts. Students were encouraged to rely on previously discussed methods and concepts. A list of the five projects and their descriptions are given below.

> **Project 1 - Trial by Teaming** (1 hour). Using unlimited materials from the kit, design an apparatus which pops a balloon in three steps.
>
> This was an introductory project conducted in a single 1-hour session during the time allocated for weekly meetings. It was designed to initiate students into the Rube Goldberg design mindset. Brainstorming and teaming to accomplish the goal as reliably as possible were stressed during this exercise. Images from the build and test sessions are given in Figures 3-7.

Figure 3 – A scene from the test session by group 1 for project 1.

Figure 4 – Scenes in sequence from the test session by group 2 for project 1.


Figure 5 – Scenes in sequence from the test session by group 3 for project 1.


Figure 6 – A scene from the test session by group 4 for project 1.


Figure 7 – A scene from the test session by group 5 for project 1.

Project 2 - KISS (Keep It Simple Stupid) Principle (2 hours). Using unlimited materials from the kit, one human interaction to start the machine, at least one energy conversion, and the least number of steps possible, activate the internal vibration circuit of a cell phone. After verification of your apparatus, please return to the meeting room for a discussion.

This project was conducted over two 1-hour weekly meetings. During the first meeting, student teams were asked to brainstorm and to design a solution to the posed problem. Construction of the project occurred during the second meeting. The planned pitfall of the project was that no construction was required according to the stated problem formulation. Students could have simply activated the phone with a button push – as they did with their construction. The goal of the project was, thus, to encourage out-of-the-box thinking that may result in an alternative, simpler solution.

Project 3 - Team Planning Documentation (TPD) Principle (2 hours). Design the most complex apparatus possible with one human interaction to start the machine and only time and safety as constraints.

This project was conducted during a single 1-hour weekly meeting session, and a 1-hour after-meeting documentation effort. During the meeting, teams were required to brainstorm and design their solution. In the second hour outside of the weekly session, teams were expected to generate written documentation of their solution (e.g. drawings) and bring it to the following session. The project was designed to contrast with project 2 with the planned pitfall of unnecessary complexity and its effects on system reliability. Further, it was unbeknownst to the teams was that they would not be constructing the solution they had designed, but rather, that of another team. Each team's work would be based on the other team's documentation.

Project 4 - Communication and Documentation (1 hour). Using only the project 3 documentation from an adjacent team, build that team's apparatus and verify the completion and outcome. After verification of your apparatus, please return to the meeting room for a discussion.

This project was conducted over a 1-hour weekly meeting. The project was designed to stress the importance of clear technical documentation as an essential product of engineering design. Each team's documentation was given to another team who was required to construct the documented solution. The planned pitfall involved the (potentially) incomplete effort that each team gave to the documentation process and the knowledge deficit that may have been created for the receiving team.

Project 5 - Putting It All Together: Planning, Teaming, and Communications (3 hours). Using a minimum of five steps, and seeking the greatest possible visual impression, each team must design an apparatus where the output of their system becomes the input to the adjacent team's apparatus. The chain of inter-team dependencies was constrained as follows. One person per team was designated as spokesperson and was solely responsible for inter-team communication.

- Team 1 actuates their apparatus at table height and their process terminates at table height plus one foot.
- Team 2 must contain the motion of their apparatus to within 2 feet forward of the actuation, and to within one foot left or right of the actuation.
- Team 3 must include motion that spans at least one meter, and the team must use the fishing rod contained in the kit.
- Team 4 must use water.
- Team 5 must use the mouse trap and must turn on a lever-type light switch.

This project was conducted over three 1-hour weekly meetings. During the first two sessions, each team brainstormed and designed a solution which met the constraints listed above. The team spokesperson communicated with the following/preceding teams in the dependency chain to understand the activation event at the interface between designs. Thus, the single point of contact between adjacent teams became crucial to the success of the entire dependency chain. A picture from the build session for this project is shown in Figure 8.

Figure 8 – Scenes from the build session involving all 5 groups for project 5.

5. Results and Discussion

The activities described in the previous section were conducted over the spring semester of 2016. At the end of the semester, students were asked to complete a survey to help the directors assess the relative efficacy of these as well as other activities undertaken by the cohort during the year. All of the twenty-seven students completed the anonymous survey. Response options were one of the following: *Strongly Agree* (SA), *Agree* (A), *Disagree* (D), or *Strongly Disagree* (SD).

The portion of the survey related to the Rube Goldberg projects and the compiled responses are given in Table 2, with the original question numbers preserved and questions grouped according to subject. Survey items were typically phrased with assent indicating a positive outcome. It can be seen that students generally had positive perceptions of the project sequence. Items 4 and 6 deal with students' overall perception of the process and the broad likelihood of a positive impact of these activities on their future careers. These items show that the majority of students had a positive view of the process. Indeed, only one student (3.7%) expressed dissatisfaction.

Table 2 – Open-ended design project survey results (percentages)
on usefulness, project management, teaming and leadership:
Strongly Agree (SA), Agree (A), Disagree (D), Strongly Disagree (SD).

Q#	Survey Item	SA	A	D	SD	SA+A	D+SD
4	I enjoyed the open-ended design projects.	59.3	37.0	3.7	0.0	96.3	3.7
6	I gained knowledge and skills that may be applied to my career from participating in the open-ended design challenges.	37.0	59.3	3.7	0.0	96.3	3.7
1	The program's PBL activities have helped me to understand project management techniques.	37.0	59.3	3.7	0.0	96.3	3.7
9	I have gained a better appreciation for documenting design work on projects.	59.3	37.0	3.7	0.0	96.3	3.7
13	Quality is everyone's job.	77.8	22.2	0.0	0.0	100.0	0.0
14	Project planning, prior to building the design, is an important step in the engineering process.	81.5	18.5	0.0	0.0	100.0	0.0
16	The documentation of design work and process is important.	88.9	11.1	0.0	0.0	100.0	0.0
2	The program's PBL activities have helped me to understand teaming techniques.	33.3	59.3	7.4	0.0	92.6	7.4
10	My project team worked well together when working on the open-ended projects.	66.7	29.6	3.7	0.0	96.3	3.7
11	When my team's open-ended design project failed, I felt responsible.	14.8	25.9	48.2	11.1	40.7	59.3
12	When our team discovered a flaw in our open-ended design, we worked to correct the design in order to make it better.	55.6	37.0	0.0	0.0	92.6	0.0
15	My PBL team members encouraged diverse points of view, openly negotiated design changes, and provided feedback to each other in order to improve team processes and project outcomes.	48.2	40.7	11.1	0.0	88.9	11.1
18	My PBL team members were flexible in thought and action in the face of challenging problems and changing situations.	44.4	51.9	3.7	0.0	96.3	3.7
19	I can complete much more work when working alone versus working in a small group.	3.7	29.6	63.0	3.7	33.3	66.7
20	I enjoy working with others to achieve a shared goal.	29.6	63.0	7.4	0.0	92.6	7.4
3	The program's PBL activities have helped me to understand leadership techniques.	40.7	51.9	7.4	0.0	92.6	7.4
5	I enjoy taking charge of a project when others stand back and watch.	14.8	48.2	37.0	0.0	63.0	37.0
7	I assumed a leadership role, in brief or full duration, in the open-ended design projects.	33.3	55.6	11.1	0.0	88.9	11.1
8	I enjoy leading others in completing a shared goal.	51.9	48.1	0.0	0.0	100.0	0.0
17	There can be only one true leader on an engineering project team.	0.0	7.4	40.7	51.9	7.4	92.6

Items 1, 9, 13, 14, and 16 (in Table 2) deal with aspects of project management including planning, quality, and documentation. For these items, the impression of the importance of project management was readily apparent. Each of these aspects of project management garnered 100% agreement across the pool of participants. This unanimous response may have followed from teams' results in project 4. Having to use another team's documentation typically resulted in unfavorable results, thus underscoring the importance of quality in one's deliverable documentation.

Items 2, 10, 11, 12, 15, 18, 19, and 20 (in Table 2) are related to teaming. Aspects of teaming encountered in the project sequence generally found strong agreement from participants (> 88%). One notable exception may be found in item 11 which asks whether individuals felt responsible when the team's design failed. Although the projects were conducted in a casual and fun setting with little impact on the academic lives of the participants, this perceived lack of shared goals and responsibility for project success presents an opportunity for improvement in future implementations of the sequence. The addition of team-based success metrics may offer a means of helping team members see past this perception.

Items 3, 5, 7, 8, and 17 (in Table 2) are related to team leadership. Most students indicated that they were given an opportunity to lead, if situationally, during the project sequence (item 7: 88.9%). Students unanimously agreed that leading others to reach a shared goal is a positive experience (item 8 – 100%). Many students did not enjoy leadership situations where they perceived that they were bearing an undue portion of the workload (item 5: 37%). Given the moveable nature of leadership within a team, either situationally or from project to project, it was clear that students agreed that leadership need not be fixed to one team member (item 17: 92.6%).

Qualitatively, the results of the survey reflect positively on the project sequence. Students generally enjoyed the projects and were observed by the directors to be engaged, cooperative, and mutually supportive throughout the process. It was also apparent during the test phases of the projects that students were eager to show their work to peers, and to see the novel approaches to the posed design problems that other teams put forward. Successful tests often were cheered loudly by the larger group. The projects generally achieved the desired goals, even in this early work. This relative success will likely influence the authors to extend and formalize the general approach for application in early PBL courses in the host department (for the course sequence shown in Figure 1).

6. Conclusions and Future Work

It has been noted that a PBL paradigm may leave some students with an incomplete mastery of concept fundamentals. Further, some students may be dissatisfied with the learning experience due to interpersonal friction associated with PBL-based team interactions.[7] The use of Rube Goldberg machines as described in this study may offer an effective means of cultivating project management and interpersonal skills which overcomes these potential pitfalls due to its low barrier to participation in terms of technical knowledge coupled with its inherently enjoyable nature. Survey results reported in the study support this claim to some extent.

This paper has presented a structured approach to the use of Rube Goldberg based projects that asks students to consider issues of project planning, time management, documentation, quality, leadership, communication, and out-of-the-box thinking. Survey results from the study generally show that the approach was effective in bringing the importance of these issues to light for the participants. It is noted that the sample group used for the study is one of uniformly high academic merit and relatively small in number. Future work will include variations in the project sequence, and parallel work with a control group composed of students from the general population of the host department so as to observe how well the approach generalizes to larger numbers of engineering students.

Limitations of the approach may be found when considering whether the experiential benefits will transfer to professional practice. The self-reported questionnaire responses may not provide a reliable objective measure. For comparison, a pre-study questionnaire as well as longitudinal (post-graduation) data generated from the cohort could strengthen the validity of the results.

As the project sequence matures, it is anticipated that these methods will be applied to freshman and sophomore PBL courses, with possible discipline specific components being added (e.g. Arduino programming and 3D printing).

Acknowledgments

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