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Teaching Introductory Electrical Engineering: Project-Based Learning Experience

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Abstract—This paper presents an integration of a loosely defined design project in an introductory electrical engineering course. The proposed project aims to introduce first-year engineering students to the world of electrical engineering and develop their general engineering skills. Because of its innovative and unconventional nature, a Rube Goldberg machine has been used as the project vehicle. In the project, students have been asked to design the machine with electrical sensors and actuators. Connected learning and assessment activities have been designed to engage students in deep understanding. Students thought the project was challenging, and could develop their technical skills and creativity.

Index Terms—electrical engineering education; project-based learning; introductory engineering; Rube Goldberg machine

I. INTRODUCTION

Because of the advancement of electronic technologies, engineers require a new set of engineering skills and system-level mindset that cannot be learned from textbook problems and traditional instructional methods [1]–[3]. Therefore, project-based learning approach [4] and other instructional methods [5] have been proposed. In project-based learning, students learn to acquire technical knowledge, solve open-ended problems without clear definitions, as well as apply new content understanding with great flexibility. Project-based learning has been shown to facilitate learning, assess students' competence in multiple perspectives, and encourage students' participation and collaboration.

Project-based learning has also been shown to be effective in electrical engineering education [6]–[9]. However, existing developed courses are usually dedicated to an intermediate or advanced topic. Moreover, the improvement of retention in engineering field as well as the development of engineering skills and attributes are a long-term cultivation, therefore, project-based learning should be introduced to the introductory engineering curriculum. To be specific, project vehicles for introductory engineering courses should be intuitive, encompass concepts about engineering, and should be related to students' everyday life. Therefore, projects in [6]–[10] are not appropriate for the introductory electrical engineering curriculum. Meanwhile, Rube Goldberg machine design project has been used to trigger and maintain students'

motivations. Besides its innovative, humorous and unconventional nature, Rube Goldberg machines are usually constituted of daily life objects, and thus the design project creates a social environment that encourages intellectual engagement.

At the same time, Hong Kong is currently undergoing a national curriculum reform, adopting the outcomes-based approach to student learning with all university degrees transforming from a three-year curriculum to a four-year curriculum. With that in mind, the Department of Electrical and Electronic Engineering in the University of Hong Kong has designed a new curriculum and adopted technologies for knowledge dissemination and teaching facilitation [11]–[14]. In particular, the department has introduced a new one-semester introductory engineering course with a Rube Goldberg machine design project module.

In this paper, we describe how a Rube Goldberg machine project has been integrated to an introductory electrical engineering course. The organization of the course is first discussed in Section II. The designed learning activities and assessment activities are then discussed in Sections III and IV, respectively. Finally, survey results and teaching observations are presented in Section V.

II. COURSE ORGANIZATION

The main objective of the course *Introduction to Electrical and Electronic Engineering* (ENGG1015) is to introduce students to the world of electrical engineering, and provide indispensable skills as an engineer. The course is a core course for electrical engineering undergraduates and an elective course for others. Since it is a foundation course, there are no prerequisites for this course. However, we expect that students know about basic electrical laws (e.g., Ohm's law). Most students (e.g., 96.5% in the Fall 2011 semester) are freshmen who do not receive any engineering training in the past.

The project involves connected learning and assessment activities that take place over the whole semester (13 teaching weeks). The schedule of activities is shown in Table I. After attending lectures, tutorials and pre-project laboratory exercises, students have to build their own Rube Goldberg machine in a group of four students. To be specific, students

have to design their machine, then implement the design with electrical sensors and actuators and finally demonstrate the machine in an in-class competition. Besides the project module, ENGG1015 also contains an instruction module which

comprehensively introduces networking, computer systems and image processing. However, the discussion of the conventional instruction module is beyond the scope of this manuscript.

TABLE I. THE SCHEDULE OF ACTIVITIES IN THE COURSE

Week	Learning Activities (Lecture and Tutorial)	Learning Activities (Laboratory)	Assessment Activities
1	Project overview; Systems; Marshmallow Challenge		
2	Laboratory preview; Electronic systems		
3	Laboratory preview; Electrical circuits (components)	Pre-project lab. (instruments)	Laboratory worksheet
4	Electrical circuits (basic analysis)	Pre-project lab. (switches)	Laboratory worksheet
5	Electrical circuits (advanced analysis)	Pre-project lab. (sensors)	Laboratory worksheet
6	Electrical circuits (power analysis)	Pre-project lab. (timers)	Laboratory worksheet
7	Digital circuits (logic gates)	Project brainstorming	Technical questions
8	Digital circuits (Boolean algebra)	Implementation/consultation	
9	Digital circuits (Karnaugh maps)	Implementation/consultation	Interim presentation
10	Digital circuits (digital systems)	Implementation/consultation	Technical questions
11		Implementation/consultation	
12		Implementation/consultation	
13			Competition/demonstration

A. Rube Goldberg Machine

A Rube Goldberg machine can be defined as “a comically involved, complicated invention, laboriously contrived to perform a simple operation” [15]. But from our technical perspective, we define it as an intuitive and loosely defined engineering system.

In the project, the Rube Goldberg machine is a machine that has at least four distinct stages with its own triggering mechanisms. In addition, the machine is started with pushing a button/switch, and is ended by popping a balloon. In a stage, an electrical sensor is triggered by an external mechanical input, the sensor then switches on the electrical actuator(s) through relay buffers. Electrical actuator then moves mechanical parts, which finally trigger the electrical sensor in the next stage.

In this project, students can to use the following components to construct their machine:

- *Electrical switches*: on/off switch, reed switch, touch switch, solid state relay, double-pole-double-throw relay;
- *Electrical sensors*: QTI sensor, rotation sensor, sound sensor, force sensor, linear position sensor;
- *Electrical actuators*: speaker, solenoid, cooling fan, motor, neon lamp, light emitting diode;
- *Mechanical parts*: trolley, metal ball.

B. Learning Outcomes

According to the accreditation from the Hong Kong Institution of Engineers [16], engineering students should be able to apply technical knowledge, design a system to meet desired needs within realistic constraints, and function on multi-disciplinary teams. To achieve the accreditation, students are expected to be able to achieve the following outcomes by the end of the project:

- Describe stages that are involved in a basic system;
- Identify electrical components and instruments;

- Demonstrate technical design and implementation skills of a basic electronic system;
- Construct timer circuits and relay circuits with latches;
- Identify, formulate and solve basic engineering problems;
- Design and conduct technical experiments, as well as analyze and interpret the obtained data;
- Work effectively with diverse teams;
- Demonstrate creativeness and communication/presentation skills.

III. LEARNING ACTIVITIES

In order to achieve each of the learning outcomes, diverse and complementary learning activities have been designed. We have taught theoretical concepts and practical skills in lectures, tutorials and pre-project laboratory exercises. In addition, we have introduced a project design facilitation tutorial and an in-class project competition. Through these activities, with building a Rube Goldberg machine as the core component, students learn in different aspects and environments.

A. Lectures

The aim of delivering lectures is to provide an overview of the “scope” and “culture” of electrical engineering. Throughout the semester, two-hour lectures have been delivered to explain selected technical basis in electrical engineering areas that are useful for students. Instead of teaching topics using a conventional bottom-up approach, a top-down system approach [17] has been chosen. In other words, high-level concepts are first explained, supplying students with the confidence, motivation and understanding needed to explore details of analyses and implementations. Lecture topics include:

- *Systems*: abstraction, top-down, bottom-up, input, output, signals;
- *Electric circuits*: basic terminology, electrical components, basic circuit analysis (Kirchhoff’s current and voltage laws), power, electronic systems;

- *Digital circuits:* Boolean algebra, logic gates, Karnaugh maps, digital systems.

Furthermore, a simple design case study of iPhone 4S has been used to link theories in different topics to everyday practice. In the lecture, theoretical concepts have been illustrated with a few practical examples.

Besides delivering technical contents, an entertaining and instructive design prototyping exercise, Marshmallow Challenge [18], has been arranged in the first lecture. The exercise requires students to construct the highest possible freestanding structure with a marshmallow on top. Since this hands-on building exercise does not require advanced engineering skills and is restricted by time (20 minutes) and materials (a limited amount of spaghetti, tape and string), it acts as a preliminary exercise for the later machine design project. The purpose of this exercise is to build up students' collaboration, problem solving and creativity, such that they are prepared for their project.

B. Tutorials

Besides lectures, tutorials have been delivered to apply taught concepts in practice. In the one-hour tutorial, theoretical concepts have been applied to solve practical problems. Meanwhile, in order to help students design the machine effectively, a project facilitation tutorial has been organized. In the tutorial, examples of machine, as well as instruments and components used in the project have been shown. Furthermore, in order to help students gain familiarity with the design process, a typical design flow has been demonstrated.

C. Pre-Project Laboratory Exercises

Besides lectures and tutorials, four pre-project laboratory exercises have been arranged to provide students with hands-on experience in working with electronic components. In the exercise, students can develop their technical skills teamwork spirit. These skills are crucial factors that contribute to the success of the project in the later stage. Furthermore, they also need to familiar equipment, components and circuits. The following topics have been covered in the exercises:

- *Equipment:* digital multimeter, voltage source terminal;
- *Switches:* manual switch, voltage-controlled relay switch, sensors (Fig. 1);
- *Actuators:* motor, lighting;
- *Digital circuits:* simple relay circuit, relay circuit with latch, timer circuit (Fig. 2).

In the beginning of each session, learning objectives have been described, the exercise worksheet has been explained, and the relevant procedure has been demonstrated. Then students had to work with groups and complete the worksheet. Furthermore, the completeness and functionality of implemented circuits have been checked, because those circuits can be used as basic modules in the project. Constructive feedback and shared experiences to students have also been given, in order to improve students' implementation skills.

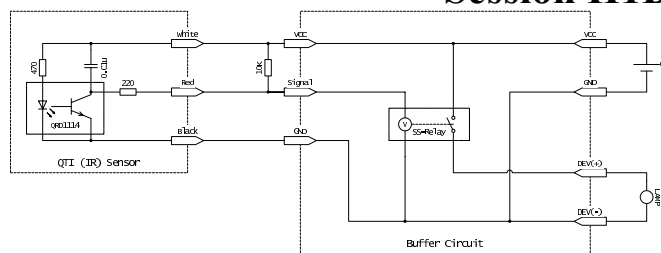


Figure 1. Layout of an implemented circuit in the laboratory: The QTI sensing circuit.

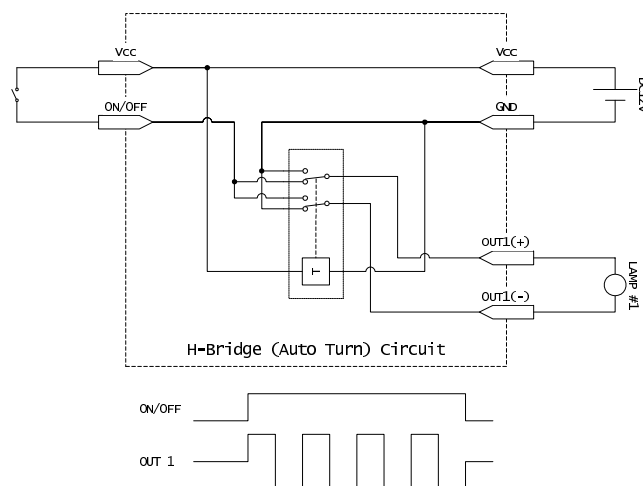


Figure 2. Layout of an implemented circuit in the laboratory: The H-bridge (auto-turn) circuit.

After pre-project laboratory exercises, optional consultation sessions have been provided. In consultation sessions, questions from students have been answered, and teaching assistants also have actively examined the working process of project groups.

D. Project Competition

The project demonstration has been structured as an in-class competition, in order to initiate students to engage in the project, as well as to have excitement throughout the course. In the competition, students have to give a five-minute demonstration to a panel formed by professors from the department. To be specific, students are required to demonstrate knowledge and skills through a live demonstration of their machine. Besides the prize associated with the competition, groups with the three highest marks will give a public demonstration in the open day of the university.

IV. ASSESSMENT ACTIVITIES

In the course, we have used pre-project laboratory exercises and an interim presentation to improve students' design skills and identify students' learned ability, respectively. Nevertheless, we have used real-world technical questions and a demonstration/competition to assess students' technical understanding and skills.

A. Pre-Project Laboratory – 30%

In view of students' different background in circuit theories, four preliminary circuit design exercises have been prepared in pre-project laboratory sessions. In these exercises, students should demonstrate their ability of using equipment and designing the layout of circuitries for sensing, driving and timing. Therefore, students have to complete a laboratory worksheet for their work. Besides examining the completeness of the worksheet, students have been asked individually about the setup and procedure of the experiment as well as the design of new experiments, such that all students are able to design and implement experiments for their projects. Students have been assessed as a group by the completeness of the laboratory session worksheet and the content of the oral questioning with an honors–pass–fail scale. Furthermore, constructive feedback has been given and weakness and potential problems in students' implemented circuits have been pointed out.

B. Real-World Technical Questions – 17.5%

In order to consolidate students' technical understanding, we have designed two individual homework assignments, which are closely related to the project. In particular, students have been asked to resolve real-world situations that may happen in their project. In order to resolve the situation, students need to analysis, synthesize and evaluate circuits, from perspectives of systems, circuits and components. Through these assignments, students have built up their debugging skills and improved their design efficiency.

C. Interim Presentation – 2.5%

After pre-laboratory exercises and the project facilitation tutorial, we have asked each group to give a three-minute presentation on their design and show us whether the proposed machine is practical. In particular, with illustrations, they need to describe the theme of the project, triggering mechanisms of each stage. Letter grades have been assigned to the whole group based on the content and the progress of the project. Furthermore, feedback has been provided to students on places that need to be improved in their design.

D. Project Demonstration/Competition – 50%

In the in-class project competition, each project group has been asked to give a five-minute demonstration. In the demonstration, students have been asked to describe the theme of the project and the mechanism of each stages. The assessment is mainly based on the functionality (50%), creativity (30%) and teamwork (20%).

V. COURSE EVALUATION

A survey analysis is used to evaluate the effectiveness of integrating the Rube Goldberg machine design project in teaching and learning. The class that studied consists of 141 students. In the questionnaire, five-point Likert-scale statements related to the course organization and learning outcomes have been posed. Besides quantitative data, open-ended feedback has been collected. In total, 108 students completed the survey resulting in a response rate of 77%.

A. Student Questionnaire

Table II shows the score distribution and the mean score of course organization that we have obtained on each of the statements. We can observe that students agree that learning activities can help them to learn and participate in the project. In particular, pre-project laboratory exercises helped them get started on the project. Furthermore, the integrative learning environment is shown to facilitate students to develop their high-order thinking.

Table III shows the score distribution and the mean score of achievement of learning objectives. Students have been asked to self-evaluate how they learned in the course. From the result, we observe that students showed confidence in their understanding of technical knowledge, from perspectives of machines (systems), stages (sub-systems), circuits and components. This implies that students learned effectively through diverse and comprehensive learning and assessment activities. Furthermore, results from Items 4 to 7 also show that from the student's perspective, students can develop their generic skills in the course.

TABLE II. SURVEY RESULTS: COURSE ORGANIZATION

Item	Responses ^a					Mean
	1	2	3	4	5	
1. Lectures and tutorials have helped you get started on the project.	4	9	13	52	30	3.88
2. Laboratories have helped you get started on the project.	1	4	8	42	53	4.31
3. Feedback from the mid-term presentation help you to improve the design.	3	7	26	29	20	3.73
4. TAs are helpful and give you useful advice.	5	3	10	50	40	4.08
5. TAs can give you high-level advice that helps you to ultimately solve design problems on you own.	5	9	17	45	32	3.83
6. This project requires you to think differently from typical classroom learning.	1	1	7	43	56	4.41
7. You will be interested in taking another project-based course that runs in a similar format like this one.	3	5	16	57	27	3.93

a. 1=Strongly Agree; 2=Disagree; 3=Neutral; 4=Agree; 5=Strongly Agree.

TABLE III. SURVEY RESULTS: LEARNING OUTCOMES

Item	Responses ^a					Mean
	1	2	3	4	5	
1. You can describe the stages that are involved in your machine.	1	0	6	42	59	4.46
2. You can describe the electrical components that are used in your machine.	0	1	7	42	57	4.45
3. You can describe the non-electrical components that are used in your machine.	1	0	6	46	55	4.43
4. You can demonstrate technical design and implementation skills that are not taught in typical learning.	0	3	16	46	43	4.19
5. Working on this project can develop your problem-solving skills.	1	1	10	45	51	4.33
6. Working on this project can develop your creativity.	1	2	14	51	40	4.18
7. Working on this project can develop your teamwork skills.	0	1	12	45	50	4.33
8. It is fun in working on this project.	2	3	15	43	44	4.16

a. 1=Strongly Agree; 2=Disagree; 3=Neutral; 4=Agree; 5=Strongly Agree.

B. Student Comments

Overall, received responses were positive. Many students thought the course is different from conventional lecture-based learning. In particular, they acknowledged the benefits of integrating a machine design project to the course. For example:

“It is a fun project. It does improve (my) problem solving skills, teamwork and time management.”

“Project is somewhat challenging, but somewhat reflects the actual practical activity.”

“Although the process of the project is hard and long, I am delighted with all the things when it success. It is a great experience.”

From questionnaire and comments, we can observe that the integrated learning environment can help students develop their generic skills. Furthermore, they found the design project was interesting because it was the first time for them to design a machine that is intuitive to build but as loosely defined as practical engineering systems. In summary, students learned and appreciated in the course.

On the other hand, students also worried about the workload involved in the course, comparing to the conventional book-based learning. Furthermore, some students mentioned that they had difficulties in identifying and solving open-ended problems that they have encountered in the implementation process. In our opinion, it is worthwhile to introduce open-ended design because this activity promotes students' creativity and helps them to think deeply into their design. Even so, we will provide more learning guidance next time to help students developing problem-solving skills effectively.

C. Teaching Observations

From what we have seen from the feedback in the laboratory, more than half of the students were enthusiastic with the project, and thought that the project was full of fun, challenging and able to give students a great sense of achievement after they have built the Rube Goldberg machine. On the other hand, a number of students felt that the project was time-consuming and the workload was heavy, and thought negatively towards the project. The disagreement between these two groups of students is quite serious. Therefore, the project should be reconstructed to encourage students' participation. Furthermore, we will continue to use the Facebook page [12] as a facilitation method to arouse students' enthusiasm of designing the machine.

VI. CONCLUSION

In this paper, we have evaluated the effectiveness of integrating a Rube Goldberg machine design project in the teaching of an introductory electrical engineering course.

Diverse learning activities and assessment activities have been designed to support dedicated learning outcomes. Evaluation results show that design project can trigger and maintain student motivations for learning of engineering. Furthermore, students have acquired technical knowledge, as well as have developed generic skills in the course. In the long term, students can apply gained experience in their future workspace, and eventually cultivate forward-looking engineers.

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