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## **IMPROVING PROJECT-BASED LEARNING OUTCOMES BY FORMATIVE ASSESSMENT AND STRATEGIC TIME OPTIMIZATION**

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### **ABSTRACT**

The 3rd year Electrical Engineering Design Studio (EEDS) course is a project-based learning (PBL) course that gives students hands-on experience with putting electrical engineering principles into practice. It is an electro-mechanical project which provides a particular challenge since electrical engineering students often lack mechanical design skills. It is found here that learning outcomes are improved by a 2-stage formative assessment and time optimization strategy that allows students to extract as much value as possible out of the limited time they have to devote to this exercise. It consists of an innovative assessment strategy that includes formal, informal and self-assessments, and an innovative budgeting, lecture scheduling, parts distribution, and order queueing system. The impact on efficiency is shown through an end-of-term student survey and a subjective evaluation of their work, in comparison to the previous year.

### **NOMENCLATURE**

PBL project-based learning

ECE	Electrical & Computer Engineering
EEDS	Electrical Engineering Design Studio
OTS	off-the-shelf
TA	teaching assistant
PCB	printed circuit board
SLA	stereo lithography
FDM	fused deposition modeling
LCR	inductance / capacitance / resistance
DOF	degrees-of-freedom
RCG	requirements, constraints and goals
CNC	computer numeric controlled
PID	proportional, integral, derivative
MEMS	micro-electro-mechanical systems
EC	electronically commutated

### **INTRODUCTION**

Project-Based-Learning (PBL) has been shown to be an effective means of improving post-secondary education [5] by combining realistic, clear goals with formative assessments. Formative assessments are an alternative to traditional end-of-

term summative assessments [2, 13] that may be streamlined by technology [1, 7, 10, 11]. Some of the reported advantages include a better and more timely understanding of goals, progress and weaknesses [3].

In engineering, PBL is a popular alternative to traditional lecture-based approaches [9] and is shown to enhance learning outcomes and student interest [8]. However, managing resources such as faculty time and design materials is a challenge which may be partially addressed by an alternative assessment strategy (electronic portfolio) [12]. High enrollments place a large burden on students, teachers and TAs but that may be reduced by assigning teams of students to work on PBL projects [4].

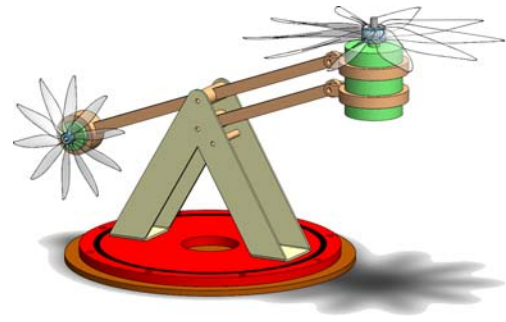
This work was motivated by a hypothesis that student outcomes in a 3rd year PBL Electrical Engineering Design Studio (EEDS) course were not wholly representative of student potential. It was limited by efficiency constraints which could be improved through formative assessment and other time optimizing strategies. Some background is provided on the course and available resources followed by a proposal which is subdivided into 2 categories, formative assessment and time optimization, each of which are further subdivided. For each sub-category, background is provided to describe the observed inefficiency, a method is described which is implemented, and the results are reported based on both circumstantial and statistical data.

## BACKGROUND

Electrical Engineering Design Studio is a required 3rd year course in the department of Electrical Engineering program at the University of British Columbia. The course takes place in the Spring term (January - April) and runs for 14 weeks, including a week-long Spring break. Each student attends 2 lecture hours and 6 lab hours per week. Students attend a common lecture but due to space constraints, lab hours are divided into 5 sections. The Spring 2015 course had a total of 154 students while the Spring 2016 course had a total of 122 students. Students work in teams of 4. For most students, EEDS accounts for 6 out of a total course load of 15 to 18 credits.

The lectures include minimal theory and focus on project management and prototyping skills. The course provides an opportunity for students to put the engineering theory they learned in other, conventional engineering courses, into practice.

In Spring 2015, the project was a 2-DOF robot arm that included a 2-DOF robot mechanism, a PID controller, a mechanically commutated DC motor and a position sensor. In Spring 2016, the project was a 2-DOF helicopter that included a mechanism, a PID controller, and an EC DC motor. A conceptual drawing of the 2016 project is shown in Fig. 1. The goal of the final demonstration was to perform a take-off,  $180^\circ$  rotation, and landing.



**Fig. 1:** Spring 2016 design project: 2-DOF Helicopter

Projects are designed to include as much breadth and encompass as much of the 3rd year electrical engineering curriculum material as possible. This includes digital, analog and power electronics, electronic devices, real-time programming, feedback control, machine design and electro-magnetics. In addition, the electro-mechanical nature of the projects provides an opportunity to instruct students on a diverse range of hands-on prototyping skills in both the electrical and mechanical domains.

The mechanical prototyping capabilities that are available to ECE students include a supervised machine shop, an unsupervised machine shop and a 3D printing lab. The supervised shop is equipped with drill presses, sanders, a band saw, a power shear, a power brake, a powder-coating booth, a spot welder and other equipment. The unsupervised shop (Thunder Lab) is equipped with bench vices, manual brakes, shears, punches, and a sand blaster. The 3D printing lab (Lightning Lab) is equipped with 5 FDM 3D printers.

More complex or time consuming parts may be ordered and prepared by a technician / machinist using equipment the students do not have personal access to. These include a CNC mill and lathe, a waterjet cutter for sheet material stock, a fully equipped wood shop, 3 high resolution SLA 3D printers and 2 additional FDM 3D printers.

All electrical prototyping is done in a fully-equipped semi-supervised electronics lab that provides 24/7 access to power supplies, signal generators, multi-meters, oscilloscopes, soldering stations, an LCR meter, and specialized equipment such as a precision scale and laser tachometer. PCB production is outsourced to a local manufacturing facility. Technical staff accumulate individual job requests and combined them onto larger panels before sending them out for weekly production. The turnaround time is approximately 1 week.

The available software tools include SolidWorks™ for solid modeling and simulation, Altium Designer™ for circuit design, simulation and PCB development, and Matlab™ / Simulink™ for modeling and simulating dynamic and control systems.

## PROBLEM STATEMENT

Mechanical prototyping and design is a skill that transcends mechanical engineering programs. Electrical and mechanical engineering projects are very often integrated since many core electrical engineering topics such as motors, sensors, control systems (robotics) and MEMS have an intrinsic mechanical design component. Mechanical design is particularly challenging in electrical engineering projects because it is a topic which few students have any prior knowledge or experience with. The 2015 offering of EEDS challenged students to build mechanical motor parts (rotor, stator, commutator), sensor components, a robot mechanism, and other associated parts such as bases and enclosures. In the end-of-term online course evaluation, the most common request was for an expansion of the course content associated with mechanical prototyping and design since it was perceived to have been their greatest obstacle.

Although student outcomes were good on average, there was a broad range of relative successes. The goal in 2016 was to simultaneously narrow the range of relative student outcomes while raising the overall average. It was hypothesized that this could be done by raising the overall efficiency of student time by formative assessment and time optimization, each of which may be divided into the following categories.

- Formative assessment
  - Formal assessment
  - Informal assessment
  - Self assessment
- Time optimization
  - Inefficiencies
  - Delays
  - Stoppages

## FORMATIVE ASSESSMENT

### Formal Assessment

A formal assessment is considered to be a scheduled, graded assessment of student work that is made after a formal or semi-formal presentation, and which is made by the course instructors.

#### Background

Large enrollments reduce the ability to provide individual attention to students. This is particularly problematic in open-ended design project courses since each student encounters their own set of unique problems that are not always suited to class discussion and certainly not to any automated resources. It is largely left to the individual to approach the professor or TA with their specific difficulties during lab times or office hours but many students are reluctant to pro-actively seek expert feedback, or do not even realize they have a problem that would benefit

from such feedback. For example, a student who is new to open-ended design often underestimates the challenges and time-frames associated with parts production, assembly and integration. The true magnitude of these tasks are often not appreciated until it is too late to respond, near the end of the project time-line.

Another common mistake made by student teams is to cooperatively work on all tasks. The reduced pressure of working all together results in a “too many cooks in the kitchen” syndrome where one member works efficiently and the others are somewhat idle.

#### Method

The inefficiencies described above are addressed by three strategies.

- Early graded formative assessment to provide an incentive to begin work early and set meaningful milestones.
- Periodic scheduled feedback to ensure all students have a realistic view of their own progress throughout the term.
- Imposed individual assessment to force a “divide and conquer” approach to taking on a multi-faceted problem.

To impose the “divide and conquer” approach, each team was subdivided into two groups of two students, a motor group and a controller group. The motor group was responsible for designing and building the EC motor. The controller group was responsible for designing and building the mechanism and control system using OTS DC motors as well a simulation. In addition, the students in each team or group were not required, and were even discouraged, from belonging to the same lab section to further promote individual work. Groups were graded independently on their motor or controller components in the first part of the course, and the team was graded as a whole on integration of the two components in the second part.

The other two strategies were implemented by a series of three evaluations that progressed linearly from a formative first assessment to a summative third assessment. The first assessment is a progress demonstration with vaguely defined expectations to allow student groups the freedom to define their own milestones. The second is a component demonstration which is expected to consist of a working motor and control system, although the state of completion is still somewhat vague since this still represents a project mid-point and not an end-point. The third is a system demonstration which should consist of an integrated motor and control system which is as complete and polished as possible and which has been accurately simulated.

The initial formative assessment is a progress review. It takes place in the 5th week and starts with an open-ended presentation of what has been accomplished. The grading rubric is non-specific and evaluates the likelihood that a group will complete on time if they continue working at the same pace. The students are asked to provide a checklist of what has been

completed as well as an estimate of whether or not they are on schedule. The assessment holds a relatively low grade percentage but a significant portion is assigned to the accuracy of their “on-time” estimate. This evaluation has the following side-effects.

- Unsolicited feedback is provided to each group. Underestimated tasks are pointed out in time for students to react.
- Students are motivated to have something substantial to demonstrate early in the term, motivating them to set aggressive milestones.
- Penalizing students for being overly optimistic in their self-assessment teaches them to be realistic about their own progress.

The second hybrid formative/summative assessment is a component evaluation. It takes place in the 10th week and starts with a semi-formal presentation of the sub-component which is expected to be complete but not integrated, so future iterations may still be planned. Each group is graded individually on their sub-component, as are individual group members for their relative contributions. This evaluation has the following side-effects.

- A milestone is set where two complex sub-components must be simultaneously ready for integration.
- Proper design processes such as defining requirements, constraints and goals must be defined to unify the two groups which have a common end-goal.

The third summative assessment is an integrated system evaluation. It takes place in the 14th and final week and starts with a formal presentation of the system, which should be as complete and polished as possible. Each team is graded as a whole on their system although individual group members are evaluated for their relative contributions. Following the summative assessment is an informal formative assessment aimed purely at guiding future activities. The formal evaluation has the following side-effects.

- The student groups are obliged to converge and function as a cohesive team.
- The students gain experience with the magnitude of a system integration task.

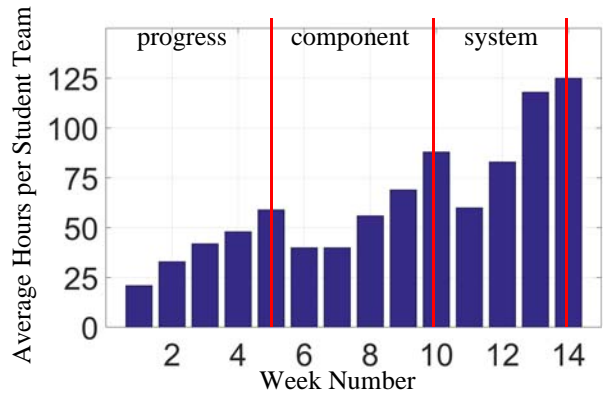
Result

The effect of the assessment method was measured by a survey question that asked students to estimate the time that was spent by all students in each team during each week of the term which had the following milestones.

- Week 5: Demo #1 (progress)
- Week 7: Midterm break
- Week 10: Demo #2 (component)

- Week 14: Demo #3 (system)

The average number of hours spent per 4-student team, as reported by the survey, are shown in Fig. 2.



**Fig. 2:** Average hours per student team per week

There is an increasing trend toward the end of the term with peaks occurring in each week that an evaluation occurs and an unusually large peak occurring in the final 2 weeks. This suggests that the periodic evaluations did entice students to devote additional time in the periods leading to them. It also suggests that the integration phase was underestimated by most students and led to the very large spike in weeks 13 and 14.

Compared to 2015, which lacked the formative progress evaluation, many more rough proof-of-concept prototypes were built, even though enrollment was lower. The early progress evaluation enticed students to use their limited time and capabilities to find creative ways to produce a rough prototype that demonstrated the concept before attempting a more refined design for the second, component-level evaluation. Although this iterative process is taught in the “Design” lecture, the first step is often skipped as a time saving measure; the progress evaluation prevented that short-cut as illustrated in Fig. 3, which shows a motor that was presented by one team during the progress and component demonstrations. The first motor is made from a bottle and screws while the second is made from the 3D printers and waterjet cutter. Fig. 3 is a representative example of the progress that was made by most teams in the time spanning the first two evaluations.



**Fig. 3:** Sample proof-of-concept and finished motor

## Informal Assessment

An informal assessment is considered to be a student initiated assessment of student work that is made by an experienced machinist or technician.

### Background

Building a physical prototype is a costly activity that should always answer a specific question. This is often not respected by students. For example, in 2015 one student team had incrementally produced more than 10 identical optical encoder disks in hopes that a new disk would cause their failing sensor to work, with no hypotheses other than manufacturing error. With a 2-day lead-time between ordering and receiving a disk, at least 3 weeks was lost to this pointless and costly exercise.

Other less dramatic examples were also common. Students would develop a set of parts intended to test a valid technical hypothesis, but would neglect to include any features to interconnect the parts. Upon receiving the parts, the hypothesis could not be tested. Only a costly lesson was learned about the basic requirements of mechanism design.

### Method

A technician with mechanical engineering and drafting experience was directed to split his time between managing the 3D printing facility and acting as liaison between the students and all mechanical prototyping facilities. Students could not order any machining services without a prior design review. This had the following side-effects.

- Unusable parts which lacked necessary features were rejected and had to be modified before being built.
- Advice for design optimization was provided to students who otherwise would not have received it.
- Students who benefitted from advising sessions began to seek advice even when it was not required of them.
- Ill-defined parts orders were rejected.

Each time a parts request is rejected, the same lesson is learned, but without the associated lead-time or material cost. For example, a waterjet part with an incorrect material specification must otherwise make it through the order queue before the machinist rejects the job. During periods of heavy shop activity, days may elapse before this occurs. Similarly, students often specify materials that are too thick to be bent in a hand brake, even though their part is intended to be bent after cutting. The same lesson is learned from attempting to bend a piece of scrap as from attempting to bend the completed part, but a scrap test has no lead time.

### Result

The number of ineffective prototypes being built was measured by two survey questions. The first asked students to identify parts that had been built in multiple iterations and to

indicate how many of those iterations were unusable or not different enough from a previous version to be useful. The second question asked students to estimate the number of times a part had been rejected and had to be re-designed before it would be made. The results are tabulated in Table 1.

**Tab. 1:** Number of built, not useful and rejected parts

	Min	Max	Mode	Mean
Iterations	2	10	3	3.6
Not Useful	0	8	0	1.5
Rejected	0	7	1	1.8

On one hand, for every part that was produced, 1.8 were rejected, corresponding to a 64% reduction in the total number of parts that were produced. In one case, a part was rejected 7 times before being built, mirroring the experience (10 optical encoder disks) of 2015, but without the associated time or material cost.

On the other hand, an average of  $(1.5 / 3.6 =)$  42% of the parts that were made multiple times, did not answer the question they were built to answer, indicating room for improvement in either the quality or quantity of the feedback. It is hypothesized that many of these unusable parts were built using the one service (free FDM) that did not require feedback before construction. In the future, an additional constraint placed on this service is expected to improve this statistic.

## Self Assessment

A self assessment is an ungraded, continual assessment of student work that is made by the students themselves and which guides them in their daily behavior. Students were not instructed how to self-assess. Instead, incentives and disincentives were introduced to elicit natural reactions by students to police their own actions.

### Background

In spring 2015, students were provided with separate budgets for SLA parts, PCBs, and electronic and mechanical components. They were not charged for waterjet parts and FDM printing facilities were not available in-house. They could however, purchase FDM parts from an independent, student-run 3D printing service. The extensive use of this service inspired the introduction of in-house FDM capabilities in 2016. Some of the inefficiencies that were noted in 2015 are as follows.

- Costly SLA printing was often used to produce large and/or simple parts due to the simplicity of 3D printing and the availability of an SLA budget, but not necessarily because of a need for high resolution or accuracy.
- Waterjet parts were ordered with little discretion resulting in overwhelming backlogs throughout the term.
- Many spare components were ordered unnecessarily

which depleted the stock, especially near the end of the term when there was available budget to be used up.

The wasteful use of resources was problematic due to their very limited nature. Only two machinists and one 3D printing technician were available to service this course, plus a 4th year capstone PBL course, plus over 250 graduate students in the department. A constant stream of 3D printing, waterjet and component requests resulted in backlogs of up to 2 weeks in duration and empty parts bins. The misuse of resources made them unavailable for legitimate requests, impacted other programs in the department, and resulted in restricted machine shop access since there were no man-hours available for machinists to supervise students and enforce safety procedures.

**Method**

An FDM printing lab was equipped with 7 low-cost low-resolution FDM printers. Two were reserved for large jobs lasting more than 3 hours and were administered by ECE technical staff. The remaining 5 were made available for hand-on student use during lab hours in an effort to relax the time demands placed on the technicians.

In addition, an integrated budget provided each team with \$1,000 that could be used toward any available prototyping services. All services had an associated cost except for FDM printing which was free if students did the printing themselves during lab hours. This had the following side-effects.

- Wasteful orders in all categories dropped noticeably. Students no longer placed orders for services simply to use up associated budgets.
- SLA and waterjet parts requests dropped to a small fraction of 2015 levels. The cost of deluxe services gave incentive to use the most economical service that would satisfy the requirements.
- Parts were designed to fit the time constraints of the free FDM printing resource to reduce budgetary impact.
- No-cost, rough, hand-machined proof-of-concept parts were far more commonly seen in the lab.

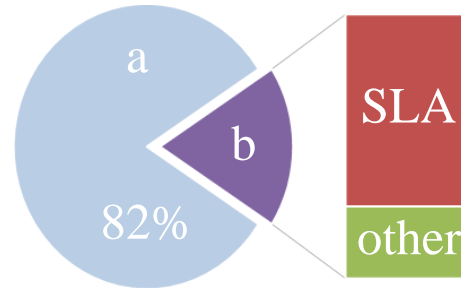
**Result**

The total number of jobs submitted by each team were tracked for each of the prototyping services and are tabulated in Table 2.

**Tab. 2:** Total number of jobs submitted

	Min	Max	Mode	Mean
Waterjet	1	5	3	3.3
FDM	0	14	0	2.7
FDM(self)	n/a	n/a	n/a	17.4
SLA	0	4	0	0.4

In addition, a survey question asked students to list the associated prototyping activities that were not done as a result of budgetary constraints. A pie chart showing the number of used (a) and avoided (b) prototyping services is shown in Fig. 4 with the avoided services further broken down to show that the vast majority of avoided services was SLA 3D printing, the most costly of all services.



**Fig. 4:** Used (a) and avoided (b) prototyping services

The free 3D printing service was the overwhelming favorite. Second was waterjet cutting which is the only service capable of producing metal parts which are necessary for certain motor components (rotors, stators) that require magnetic material properties. Third was billed FDM printing which was usually used as a second line of defence when the competition for free FDM printing became too great. Last was SLA 3D printing, the most expensive service, which was used for small, precision parts, such as motor/propeller adaptors and other components.

The integrated budget proved to be a highly effective mechanism for enticing students to self-police their own wastefulness. The popularity of each service was strongly associated with its relative cost. The free service was used by default, with all other services used only when their particular advantage was required. In fact, a student survey question revealed that 242 out of a total of 539 parts (45%) were specifically designed to be printed within the 3 hour free FDM time window.

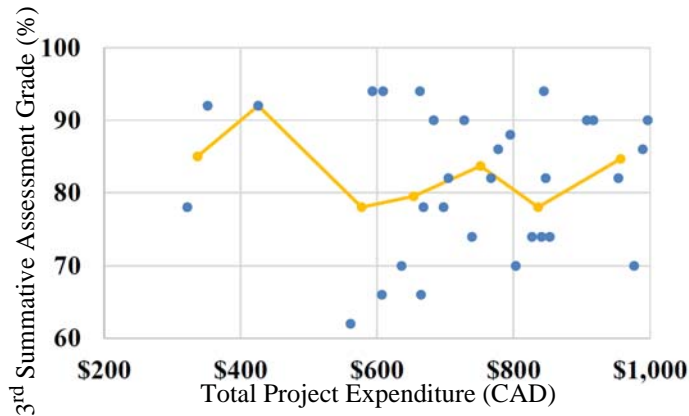
The only example of serious waste that persisted was something they were not charged for, the choice of waterjet materials. In a few cases, expensive, thick acrylic was used for structural parts, strictly for its aesthetic appeal. This is an obvious opportunity for future improvement.

A scatter-plot of the marks that were awarded to each group in the third summative assessment, against their respective total expenditure is shown in Fig. 5 with the average mark for each \$100 increment drawn as a solid line.

There is no obvious grouping or correlation between the 2 axes, and the trend line is essentially flat and noisy. Unlocking a student’s potential does not seem to be strongly affected by available budget, although a reasonably generous budget does encourage experimentation. In another student survey question,

**Tab. 3:** Spring 2015 & 2016 lecture schedule

	Topic	2015	2016
	<i>Overhead: Course info</i>	1	1a
A	Design & RCGs	1	1a
B	How to get started	2	1b
C	3D printing & waterjet	3	2a
D	SolidWorks I: Solid & Sheet	4	2b
E	Electrical Prototyping	5	3a
F	Altium I: Circuit Design & Sim	6	3b
	<i>Overhead: Progress</i>	n/a	5a
	<i>Overhead: Component Demo</i>	8	10
G	Mechanical Prototyping	9	4a
H	SolidWorks II: Assemblies	10	4b
I	Altium II: PCB Layout	11	5a
	PCB Production	12	11
	<i>Overhead: Final Demo</i>	14	14



**Fig. 5:** Final project grade vs expenditures

each team designed an average of 2.9 motors and 2.4 working motors with 4 teams reporting having developed 5 working motors. They were only required to build 1 working motor but the desire to improve, paired with an availability of budgetary support, encouraged iterative development and reinforced the experience for many students.

## TIME OPTIMIZATION

### Inefficiency

An inefficiency is considered to occur when a student lacks the sufficient skills or knowledge to perform a task quickly or correctly enough that it will not have to be repeated later.

#### Background

Perhaps the greatest source of inefficiency occurs when a need to perform a task precedes the lecture hours that are devoted to present it. It is most prevalent in team-based projects where multiple tasks are taken on in parallel, each with different educational needs that cannot all be satisfied at the same time.

The EEDS course is allocated one 2-hour lecture at the beginning of each week in the term. The associated lectures may be divided into 2 categories, overhead and technical. Overhead lectures are used to present topics related to the administration of the course. They are distributed throughout the term, as appropriate. For example, instructions that outline the associated evaluation and grading rubric are given prior to each project evaluation.

Technical lectures cover engineering design principles and practical skills related to producing a working prototype. They include the topics shown in Table 3, each of which was delivered in the week indicated in Spring 2015 and 2016. Note that the topics were consistent but the scheduling was different. All technical topics are annotated (A through I) for future reference. “PCB Production” was an informational lecture that did not teach a hands-on skill and no lectures are scheduled in week 13 to allow students time to complete their projects.

The 10 technical subjects are arranged in perceived order of importance. For example, a lecture on getting started is delivered right after students have had sufficient time to organize into groups, divide the tasks, and define their project in terms of RCGs; a set of initial steps are presented for each task so that no student is left idle, wondering how to get started.

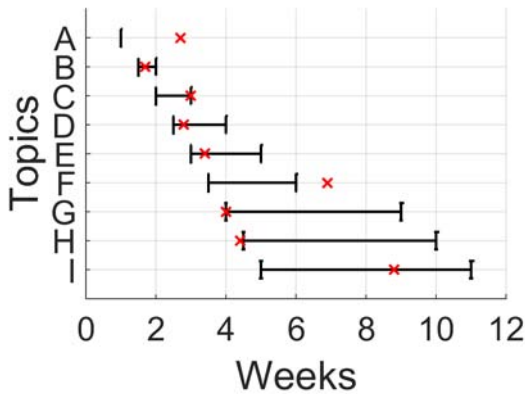
Since most tasks include a mechanical design component which Electrical Engineering students have little experience with, the fundamentals of mechanical prototyping are scheduled next. All students have pre-requisite experience with electrical prototyping from their second year project course and arrive capable of breadboarding circuits. More advanced topics on electrical prototyping are therefore less time sensitive.

Although the order of topics is optimized in 2015, students are instructed to begin working on a proof-of-concept prototype in the second week but SolidWorks is not presented until the fourth week, leaving them to learn it on their own. Time is spent searching through online tutorials, of which there are many, and the tutorials they choose do not always cover the relevant software features or proper design techniques. In any case, they do not get a unified, optimized set of instructions that are focused on their expectations and available resources. Consequently, their work is less efficient until after the lecture takes place where any misdirections may be pointed out and corrected.

#### Method

In Spring 2016, student efficiency is improved by scheduling an additional 2-hour time slots in each of the first 6 weeks of the course, in exchange for cancelling some of the later time slots. This resulted in the schedule shift shown in the “2016” column in Table 3 which is graphically portrayed in Fig. 6 where the right

tick corresponds to the 2015 delivery date, the left tick corresponds to the 2016 delivery date, and the technical topics (A-I) are as indicated in Table 3. Each “x” denotes when the students began exercising the presented skill. Note that the last three technical topics are delivered 5-6 weeks earlier in 2016 than in 2015.



**Fig. 6:** Graphic comparison of subject delivery dates

Combining the feedback provided during the formal and informal assessments with an earlier lecture schedule allowed lecture material to be reinforced during feedback sessions, using the students’ own work as examples to learn from, and resulted in the following side-effects.

- Software tools were used effectively throughout the project since students learned them in context and early in the term, usually before needing them.
- An increase in overall quality was identified in the component-level evaluations since students had ample opportunity to practice the skills taught in class.
- An increase in overall quality was identified in the system-level evaluation since a higher quality of engineering design work was accomplished in the time allocated.

### Result

The associated efficiency improvement was measured by a survey question which asked the students to estimate the week in which the skill taught in each technical lecture had been put into practice. Fig. 6 is annotated with an “x” to indicate the average for each technical skill. Except for topics A, C and F, students worked inefficiently, sometimes for over 5 weeks (G, H), in 2015. The only reason topic C (3D printing) was not used right away in 2016 appears to be because topic D (SolidWorks I) was required before topic C became useful. This is another obvious opportunity for future improvement.

Topic F (Altium) was not used significantly until after the component demonstration, when they began integrating their circuits, suggesting that it might be prudent to move it after topic

H (SolidWorks II) in the future. Topic A (Design) was not used significantly until the 3rd week which suggests that the message was not very well received. It is proposed that the delivery of this material be revised for future iterations of this course to improve student understanding of the formal design process and the benefits of defining the problem before settling on a solution.

### **Delays**

A delay is considered to occur when a student is required to wait for a period of time before resuming a task, although other tasks may be performed in the meantime.

### Background

An in-stock supply of OTS components is provided that includes a collection of both electronic and mechanical components. A list of available components is provided online to students who may order the parts and have them delivered by a TA. The parts are replenished regularly by technical staff to maintain a reasonable stock. This parts inventory is an integral component of the open-ended nature of the EEDS course. Students do not receive a prescribed collection of “parts to be assembled” like a jigsaw puzzle. Instead, a menu of commonly used parts is made available, from which they can choose to solve their project requirements, similar to an online parts catalogue in a real-world problem.

In Spring 2015, a dedicated parts TA would collect and fill parts orders once a week. The lead-time caused substantial delays, especially when a weekend was lost waiting for parts to be delivered. On many occasions, students would travel off-campus to local parts stores to avoid this delay, which involves a large time investment, particularly when public transit is the only travel option, as is the case for many students.

### Method

A large, locking parts cabinet was installed in the project lab to house the parts stock. All TAs who supervised labs were trained to distribute parts and record costs on the spot, during all lab hours which spanned 30 hours each week. This had the following side-effects.

- Parts were distributed with virtually no lead-time.
- Less time was devoted to acquiring parts from off-campus vendors although students did still go online or off-campus for non-standard parts.

### Result

The associated time saved was measured by asking students to provide the following two estimates.

- The time between when they chose a component and when they received it (“Chose → Received”).
- The time between when they received a component and when they began using it (“Received → Used”).



The results are tabulated in Table 4.

**Tab. 4:** Component lead times

	Min	Max	Mode	Mean
Chose → Received	0	5	1	1.2
Received → Used	0	5	0	0.6

The modes and means indicate an approximate 1 day delay for receiving a desired part with almost no time elapsing between receiving and using the part. Even the maximum reported delay of 5 days is less than the 1 week lead time which was the norm in 2015. This indicates that almost any time lost to parts distribution inefficiency is a source of student progress delay.

### Stoppages

A stoppage is considered to occur when a student is required to wait for a period of time before resuming a task, and is prevented from performing any other task in the meantime.

### Background

The high demand for free FDM printing introduced an unanticipated stoppage. Student access was allocated first-come first-served, beginning at the start of each 3-hour lab session. During high volume periods, such as the days preceding an evaluation, students would congregate outside the 3D printing lab to wait for it to open. The students in Fig. 7 had begun lining up at 5am for a 9am opening. Although a chair is used as a makeshift desk, this is a poor work environment where little, if any, progress is possible.



**Fig. 7:** Students lined up for free FDM 3D printing

### Method

An online queue system was developed with the following features.

- A job request containing the team number and job duration is entered into the queue.
- Only 1 job per team is accepted. If a second job is entered by a team, the first job is deleted.

- Only jobs with a duration less than 3 hours are accepted.
- The cumulative print time of each team is recorded and used to sort jobs. First priority is given to the team with the lowest accumulated print time. Second priority is given to the earliest queue entry.

At the beginning of each lab period, students demonstrate to a TA that the print time of their job matches the print time entered in the queue. A token is then provided which grants access to a 3D printer to run their job.

A job is removed from the queue when

- the print job has been completed,
- the student is 15 minutes late,
- or the printing lab closes at the end of the day.

The print queue was deployed at the beginning of week #11 to eliminate stoppages during the integration phase of the project. From informal discussions, the online queue was well received. It also encouraged TAs to arrive to the lab on time since all printing would be delayed if they were late.

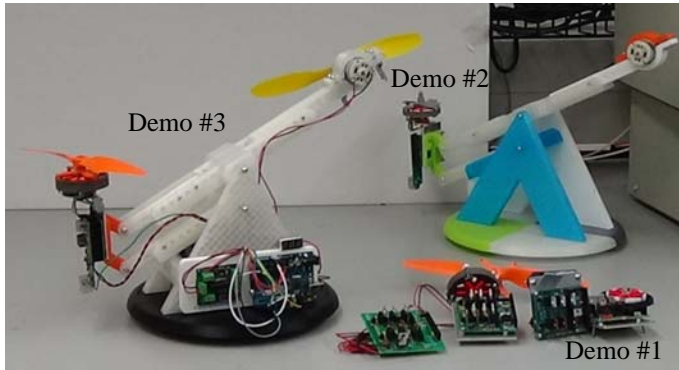
### Result

Students were asked to estimate the amount of time spent waiting in line before the queue was created. The average stoppage was reported to be 5.7 hours. With 31 student groups, this corresponds to a total of 177 student-hours for the first two evaluations. Since the queue was active for 3 weeks (11-13) and inactive for the previous 9 weeks (1-6, 8-10), it is estimated that approximately  $177/3=59$  student-hours of stoppage was prevented by deploying the queue in week #11.

### CONCLUSIONS

It is demonstrated here that PBL learning outcomes are strongly correlated to how well the efficiency of student time is optimized. The time optimization techniques and related results described here are as follows.

- A series of regularly-spaced formative, semi-formative, and summative assessments motivate students to set early, aggressive milestones and to follow good incremental design practices such as the three submissions shown in Fig. 8. In addition, regularly-provided expert feedback helps to re-direct misguided students when there is still time for a meaningful response.
- Imposing informal assessments before building prototypes has a strong positive impact on reducing lead-time and material cost without any degradation of the student experience.
- An integrated budget is an effective means of getting students to self-police their own inefficiencies. They produce fewer unnecessary prototypes and make efficient choices about the appropriate prototyping technology to



**Fig. 8:** Progression of demonstrated results

use.

- Technical lectures on hands-on skills have an almost immediate impact on efficiency and should be scheduled as early as possible, especially with skills that expand breadth.
- Timely availability and delivery of components has an almost immediate impact on student efficiency.
- A backlog that causes students to physically queue, causes long work stoppages that may be eliminated by a simple online booking system or other means.

The average overall grade rose from 76% in 2015 to 83% in 2016. A 7% increase corresponds to almost an entire letter grade of improvement. The project and facilities were consistent, as were the faculty and staff involved. The fundamental changes were those described here which focused on student efficiency.

Of the three time-optimization categories, the one with the greatest impact was found to be inefficiency since it affected all students for the longest duration and resulted in work that had to be repeated. Delays did not stop progress but affected a large number of students and reduced the number of design iterations that were possible within time constraints. Although stoppages did halt progress, they were constrained to a specific task and only affected a subset of students.

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