Paper ID #25549

Iron Range Engineering - An Overview of Design and Open-Ended Problem Solving Activities in an Interdisciplinary, Project-based Learning Program

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Introduction

“Empower you to become the engineer that you want to be.”

Engineering education is at a point of change. Many engineering education practitioners have shown interest in evidenced-based methods of developing student engineers, such as project-based learning, experiential learning, peer to peer learning, and game-based learning. This paper describes an engineering education program that emphasizes technical, professional, creative design skills in our 3rd and 4th year student engineers. This program is continuously improving. Faculty and staff meet each semester to reflect on the prior semester, address student feedback, and make specific changes to improve. Learning science tips are weaved into the dynamic program. Motives are pure, but execution can have some challenges. This program’s philosophy allows faculty to try, get feedback, and pivot. Faculty exemplify iterative design and the freedom to fail upwards in a very transparent way. Faculty also role model professional behavior and continuous improvement strategies for student engineers. We believe this authentic being is helpful in our students development as self-aware, reflective, life-long learners.

Iron Range Engineering (IRE), a program of Minnesota State University-Mankato is entering its 10th year. Student engineers transfer in from community colleges, complete their 3rd and 4th years, and earn a Bachelors of Science in Engineering degree in the off-campus program location. As of Jan. 2019, 160 student engineers have graduated from the project-based learning (PBL) program and 95 percent have found successful employment within 6 months of graduation. Other papers have documented various aspects of the program over its first 9 years. The purpose of this paper is to describe the current state of the integrated teaching and learning strategies that the program uses to facilitate engineering design learning with an entrepreneurial mindset in a PBL model.

Awareness of the IRE program has increased recently with the program being recognized as the ABET 2017 Innovation award winner and in the top ten emerging leaders in engineering education in the “Global state of the art in engineering education” report by Dr. Ruth Graham released in 2018 [1].

Purpose of research

The purpose of this paper is to describe how the Iron Range Engineering (IRE) program leads student engineers to ”become the engineer they want to be” by working with industry design projects, scaffolding for the design process, mentoring, facilitating learning in technical competencies, and the practice and assessment for selected fundamental principles of engineering. This program changes every semester through strategic continuous improvement. Since the program was recently awarded the ABET Innovation Award and was named one of the top ten emerging leaders in engineering education worldwide by the MIT-sponsored report written by Dr. Ruth Graham, it seemed appropriate to share the program’s current practices with the wider engineering education community. While the ”recipe” for this program is not 100 percent replicable, many aspects can be adapted to other courses and programs. We describe here the design process, the innovation process, the structure and format of technical competencies, and active learning strategies used at IRE. The faculty and staff at IRE look to continuously improve; our intent is to share our best practices with others and anticipate that they will find valuable ways to improve their teaching and learning as well.

Program context

The job of an engineer is to create value for people. The best way to acquire the professional and technical skills necessary to become an engineer is to experience, first-hand, what it is to be an engineer. To accomplish this goal, students in this program complete a series of industry-sponsored projects that form the core and foundation of their engineering education. These projects include facets of design, manufacturing, procurement, industrial safety, reliability, process improvement and even finance and marketing/sales. Students acquire engineering knowledge in context with the industry projects as they earn 1-credit technical competencies. Generally, learners spend 40 hours per week on campus in an office/consulting firm atmosphere learning engineering design by actually providing value to client industries. Approximately 20 hours per week are dedicated to design project execution and 20 hours per week in learning technical content and professional skills, with synergy between them. Students learn how to be an engineer by doing engineering work. Projects grow in size, scope, and complexity throughout the education experience, with 3rd and 4th year student engineers serving as peer mentors to 1st and 2nd years learners from an affiliated community college assigned to their teams. Students work in a true multi-disciplinary environment, serving in a variety of functions that range from product development to manufacturing, project management, communication, and teamwork. The projects address authentic problems for industry partners, and students learn while managing true constraints and client deliverables. Throughout these projects, students are coached by professionals from the fields of engineering, business, management and education. This collaborative mentoring process exposes students to the professional and technical skills needed to become effective communicators, problem solvers and, ultimately, successful engineers. The project-based learning approach with a focus on communication, professionalism, and entrepreneurial mindset results in high-quality preparation for the rigorous expectations that industry and society place upon our graduates.

Background

Several papers have reported on the initial development and progress of IRE program. The motivation and early years of IRE are documented in Ulseth's 2016 thesis [2]. This includes a comprehensive review of the literature on relevant learning theory. The process of change management activities as the IRE program developed as a program of a larger university is discussed in Allendoerfer et al [3]. Entrepreneurial mindset in the program has been described by Pluskwik [4] and Ulseth [5]. Gamification activities have been summarized by Pluskwik and Leung [6]. A description of complex and ill-structured industry problems is presented by Marra [7], and external satisfaction survey results from graduates and their employers can be found in Johnson and Ulseth's paper [8].

Learning Theories in practice

Learning science informs the program's continuous improvement model. As researcher Dr. Ruth Graham wrote in the recent "Global state of the art in engineering education" report [1], institutional leadership and a strong commitment to evidence-based learning pedagogies in engineering education, as well as innovative, forward-thinking approach shared by faculty and the institution alike, are important for engineering education to improve. This program is based on those beliefs. The program is also grounded in John Dewey's proposition that higher education is to assist individuals in developing the skills to be effective in their preferred occupation. This program focuses on developing professional competencies such as people and project management,leadership, and ethics, as well as perseverance, stress management, and the ability to reflect and modify one's process of learning. Treveylan's [9] studies on "the work that engineers do" call for more emphasis on professional skills such as communication and the ability to perform effectively on teams. Treveylan advocates for students teaching others because "education, like engineering practice, relies on special kinds of social interactions" and that students learn when they have to explain to "others using such methods as cooperative learning and peer instruction". Carol Dweck's work on growth mindset [10] and Angela Duckworth's suggestion to connect effort with outcomes to motivate "grit" in learners [11] both underpin this program's learning activities and values.

The three components of Deci and Ryan's self-determination theory [12], which are autonomy, relatedness, and competence, are the basis of many of the program's features; these are designed to enhance internal motivation to manage and improve one's own learning. Students are given choice and flexibility to "become the engineers they want to be" along with tools such as a dashboard to monitor the effectiveness of their learning processes, seminars on professional expectations, and many opportunities to interact with engineers from industry.

The program has also benefited from guidance from other leaders in engineering education. Jeffrey Froyd, Alan Cheville, Denny Davis, and Edwin Jones have all provided recommendations that have been incorporated into the model. The work of John Heywood and Arnold Pears in evidence-based teaching as scholarship, John Cowan in verbalizing thinking during problem solving and reflection journals, and Annette Kolmos in project-based learning, and other engineering education leaders have influenced this program significantly.

Typical Learners in the Program

Students transfer in to the program in their third year of college and are typically graduates of a community college. Each applicant to the program is interviewed by the Program Director and writes an essay. Preferred qualifications include a growth mindset and an interest in project-based and self-directed learning (subjectively evaluated via the interview). A cohort of Junior 1 learners (J1) starts each semester; total enrollment is capped at 50 learners in upper division (J1 to Senior 2) per year. The incoming student engineers are not cream of the crop students. They are bright to average mostly local students who become high-quality engineers in just two years by doing engineering work in an intensive learning environment, supported by professors who care a great deal about learners' readiness for a successful entry-level job placement and career. The selection process has not changed much since inception of the program. Some research has been done on the factors that lead to upper division success in PBL programs, such as lower division GPA. So far, no significant findings in predictive factors have been found. Christine Kennedy, Director of IRE, states that we cannot necessarily predict who will be successful, but the program does have a 95 percent graduation rate, and 95 percent of graduates are working in their position of choice within six months. The majority of seniors have accepted full-time job offers before graduation, due to extensive job-search workshops and realistic Interview Nights every semester and co-operative learning experiences. External validation of student attainment of the typical ABET-identified professional competencies is recorded in Johnson and Ulseth [8].

Multi-disciplinary learning is emphasized, including a broad base of engineering "core competencies" including entrepreneurship. Project teams of 3 - 5 learners are vertically integrated from Junior 1 through Senior 2, as well as disciplinary integration; electrical engineering focused students are on the same project team as mechanical focused learners.

The program is ABET accredited and has added student outcomes related to people and project management, entrepreneurship, and inclusivity in addition to the traditional ABET student outcomes. The program includes a broad breadth of student experience, including co-op experiences and Study Abroad. Learning is accomplished in a blend of face-to-face and online methods of delivery. Peer learning is emphasized.

The following sections describe the current Design courses for the 3rd and 4th year student engineers, the open-ended problem-solving processes, and increased use of game-based learning activities for long-term retention of fundamental principles of engineering. Student reflections and assessments follow.

Design Course

Students perform design, teamwork, and project management tasks every day to add value to the company and to help maintain or enhance the company's competitiveness.

Student engineers enroll in a 3-credit design course each of four semesters in their 3rd and 4th years in the program. The Design course is co-taught by two faculty with both 3rd and 4th year learners together. Seniors have a higher level of performance expectation, including leadership on their project teams. In Design, student engineers learn and practice the essential elements of engineering design: scoping, modeling, experimentation, analysis, use of modern tools, multi-disciplinary systems view, creativity, safety, business plans, and global/societal/environmental impacts.

The project problems are sourced from industry clients or proposed by student engineers. Student teams of 3 -5 members each write a Team Contract, occupy Project Rooms, and work together approximately 15 hours per week to complete the project each semester. They select roles such as Project Manager, Client Communications, Documentation Manager, and Research Manager; they plan and carry out the Work Breakdown Structure tasks in the project management plan and often use a “Do-Doing-Done” agile work board as well as overall project Gantt Charts to track their progress through each sprint. Research findings, meeting notes, drawings, and other project work is compiled in a binder, and teams write a technical project report, which is generally 30 - 80 pages in length. An executive summary is also written for the client. Each project team is guided by a facilitator.

Sprint Model

An important change was implemented in the four-semester Design sequence in Spring, 2018 to include more focus on agile project management by student engineers. Rather than one long design process over a semester, the semester is divided into three sprints, each being 3 - 4 weeks in length. Each sprint culminates with a design review, a solution which may be a minimum viable prototype, a technical document and drawings or other client deliverables, and a presentation to faculty and peer student engineers in the program. During the following sprint, project team members iterate the design process to achieve a more refined solution. This change was made to avoid the lull in student effort and documentation that commonly occurred during the middle of the semester. Faculty and students feedback indicate that the sprint model has resulted in improved student motivation, interest, and completion of deliverables achieved earlier and with less stress experienced by the students. We continue to use the Sprint model.

Facilitator Role

The role of the facilitator in the IRE program is primarily a coaching function. The entire program is designed around project-based and self-directed learning, so it is critical that project facilitators actively engage students, encourage open and honest communication within the team and build social capital among the team and themselves. Psychologist Carol Dweck’s work on growth mindset, attitudes toward error, self-talk, and the role of positive mentoring informs the facilitation role [10]. Coaching enables facilitators to leverage years of professional experience to improve the quality and effectiveness of learning for students. Coaching is a two-way communication between the facilitator and the learner. The feedback loop and empathetic support are both critical roles in the facilitator-learner relationship. Facilitators are compensated and generally spend 10 hours per week meeting with the team members, attending a weekly Facilitator Meeting, providing feedback to learners on project management, technical learning and design decisions, and reflection journals, and serving on Design Panels. Facilitators complete a Performance Review on each team member each semester.

Design review format and expectations

The design reviews provide time for a panel of faculty members, facilitators, and engineer guests to ask tough questions that challenge the students and help them grow and advance their project solution. Each panel design review lasts 45 minutes and has the following goals:

- Evaluate design solution against requirements, constraints, and objectives
- Verify that work activities are achieving planned outcomes
- Identify issues to be addressed
- Discuss reprioritization of work
- Commit teams to future work activities

For example, Sprint Design Review #1 focuses on how well the team has done the following tasks:

- identified the driving forces behind the project determined and met appropriate, measurable constraints and objectives in order to solve the client's problem
- applied research and creativity to generate options and made sound decisions to narrow those options down
- chose and communicated suitable engineering principles that drive solutions
- selected and completed appropriate, value-adding deliverables for the client
- formed a project management schedule to complete the project in the allowed time
- created next steps for Sprint #2.

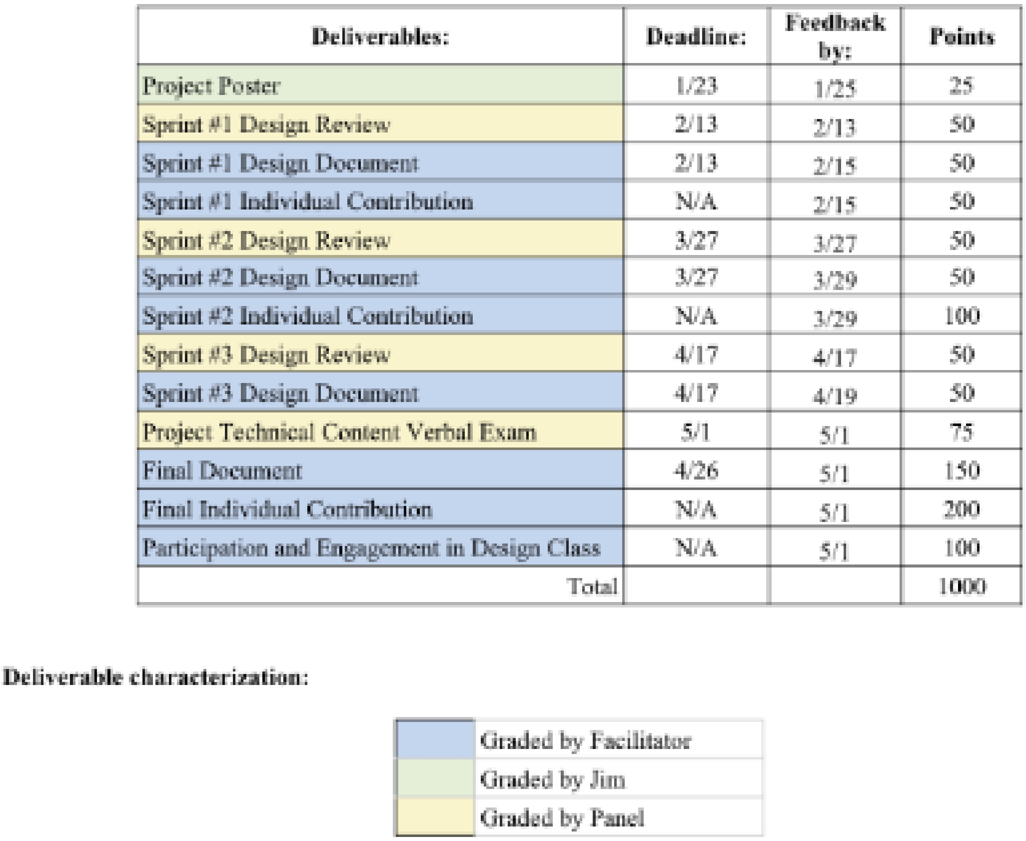
Over the course of each semester, three design reviews are held, one following each Sprint. Students defend the work done and communicated learning achieved. Scoring rubrics are used. General project expectations for design reviews include timeline progress, quality and quantity of research, quality and quantity of documentation, usage of design process, and creation of value for the stakeholders. Students identify their project's problem statement, functional requirements, technical requirements, financial requirements, and social requirements. Solution expectations include risk assessment, modeling and analysis, solution prototyping and testing, solution verification and refinement, and creation of value for the client. Expectations increase with each succeeding Design Review. All team members are expected to be ready to defend the technical aspects of the team's solution. Peer-to-peer teaching and learning is scaffolded in this way.

Project teams give several presentations each semester to practice communication to various audiences. Students in the audience provide written feedback to peer groups to help develop their skills in active listening and their ability to provide constructive feedback.

After a morning of design reviews, all evaluators meet in a closed meeting and discuss overall performance of the teams. They also write their recommended scores on a grid on a whiteboard, so grading consistency can be verified.

Assessment in Design

Project work is graded collaboratively by the Design course instructors, the facilitators, and the design panel members. Most project work is graded as a team, and individual contributions are assessed by instructors and facilitators to increase or decrease an individual learner's grade, as shown in Figure 1.



Deliverables:	Deadline:	Feedback by:	Points
Project Poster	1/23	1/25	25
Sprint #1 Design Review	2/13	2/13	50
Sprint #1 Design Document	2/13	2/15	50
Sprint #1 Individual Contribution	N/A	2/15	50
Sprint #2 Design Review	3/27	3/27	50
Sprint #2 Design Document	3/27	3/29	50
Sprint #2 Individual Contribution	N/A	3/29	100
Sprint #3 Design Review	4/17	4/17	50
Sprint #3 Design Document	4/17	4/19	50
Project Technical Content Verbal Exam	5/1	5/1	75
Final Document	4/26	5/1	150
Final Individual Contribution	N/A	5/1	200
Participation and Engagement in Design Class	N/A	5/1	100
Total			1000

Deliverable characterization:

🟦	Graded by Facilitator
🟩	Graded by Jim
🟨	Graded by Panel

Figure 1: Assessment summary from Design course syllabus, Spring, 2019, shows point allocation for various deliverables and contributions to project completion.

A new question was recently developed by a faculty member: "On the IRE Scale, how would you rate the team's performance, relative to it's potential?" (IRE Score is 1 - 5, with 5 being

“Exemplary”.) A team was posed with this question in Spring, 2019; 75 percent of team members answered “Acceptable (3) ” and 25 percent said “Needs Improvement (2)”. The Facilitator will have a discussion with the team on whether they want to close the performance gap or if they are satisfied with that score and performance. We anticipate this question to be motivating, as the evaluation is intrinsic, reducing the negative emotion often associated with professor or facilitator giving all the scores.

The Project Technical Content Verbal Exam is a new assessment being implemented in Spring, 2019 to encourage project-related technical knowledge transfer between team members. All team members should wholly understand the technical aspects of the project. Prior to Spring, 2019, individual members were encouraged to share their own technical learning from the project with team members, but this was not assessed as a team. This new exam is a low-stakes group exam done at the end of each semester, one team at a time, and is assessed by an invited subject matter expert and a faculty member. The facilitator holds practice “exams” in weekly Team Meetings. In this exam, each team member is expected to defend technical work done by any member of the team.

Fundamental Principles

Student engineers are expected to base their design solutions on a set of fundamental principles of science and engineering. To prepare students for this application, faculty have identified a finite set of fundamental principles, which are introduced and practiced in the 20 core 1-credit technical competencies that are required of all students in the program. See Appendix A for the current list. Students are expected to regularly retrieve this knowledge through self-quizzing, group review sessions using FE exam-type questions, and other game-like activities, as described in the 2018 ASEE paper by faculty members Leung & Pluskwik [6]. This regular retrieval of fundamental principle knowledge helps students retain their growing body of knowledge, thus pushing the forgetting curve further into the future, as Ulrich Boser describes in his 2017 book “Learn Better” [13].

Additional fundamental principles stem from students’ selected advanced competencies. The list of fundamental principles used in this program was developed by the faculty members who teach these competencies. They were asked to consider the most important, basic concepts or principles upon which the rest of the knowledge is based. For example, the First Law of Thermodynamics underpins much of related heat transfer knowledge, so that is deemed to be a “fundamental principle.” We acknowledge that a wide variety of fundamental principles in engineering exist. We used the expertise in our faculty group to come up with the core principles that they feel best ground the knowledge in their areas of expertise. The list is finite in our program so it is not overwhelming to learners, is reviewed periodically by faculty, and comprises the fundamental knowledge that learners in this program will be expected to remember until graduation and hopefully well into their engineering careers. Design decisions are expected to be based on the fundamental principles, and a verbal Fundamental Principles exam is taken each semester. The Fundamental Principles exam is described in the Assessment section of this paper.

Open-ended problem-solving practice

Upper division students participate in a Creative Innovative Open-Ended Problem Solving (CIOPS) process each semester, delivered in a one-credit Seminar course that meets for one hour per week. In CIOPS, students take part in various workshop activities to increase creativity, sketching, and problem solving skills. They complete a verbal CIOPS exam each semester, in which an open-ended problem is chosen by the learner from a pool of appropriately scoped problems. Students step through the design process to generate different solutions for said problem in a 24 hour period. Ten hours of time on task is outlined and expected. They present their process and solution to a panel in a one-hour verbal exam, as shown in Figure 2.

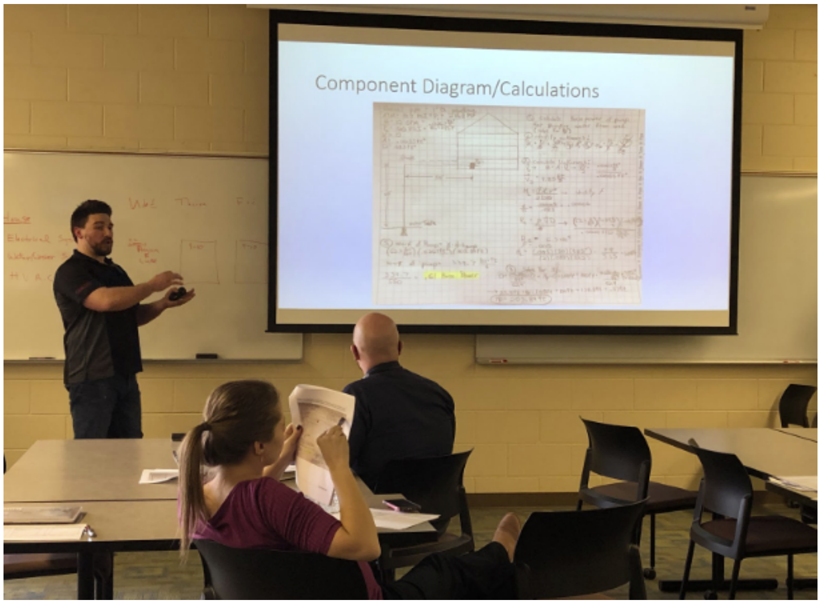
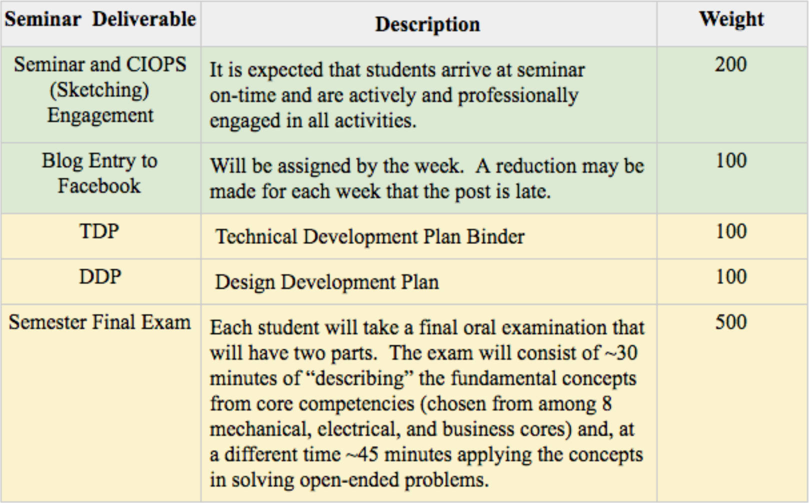


Figure 2: Student presenting his design process, refinement, and solution during his Creative, Innovative Open-Ended Problem Solving (CIOPS) exam for a panel of faculty and facilitators. Each student does a CIOPS exam four times, one each semester in this upper division program. Students write a reflection following each exam; the reflection score is a major component of the exam grade.

The CIOPS, the Fundamental Principles exams, and the reflection together make up the Seminar Final Exam, which is 50 percent of the overall Seminar grade, as shown in Figure 3.

Active learning methods used to teach engineering design, technical knowledge, and professional skills

The IRE model is based on self-directed learning (SDL) that includes research, project work, individual studies, and reflection. Questions surface throughout this process that are technical, professional, social and ethical in nature. It's at this point of "demand" of knowledge that instructors can deliver targeted content relative to the student's question. This creates an



Seminar Deliverable	Description	Weight
Seminar and CIOPS (Sketching) Engagement	It is expected that students arrive at seminar on-time and are actively and professionally engaged in all activities.	200
Blog Entry to Facebook	Will be assigned by the week. A reduction may be made for each week that the post is late.	100
TDP	Technical Development Plan Binder	100
DDP	Design Development Plan	100
Semester Final Exam	Each student will take a final oral examination that will have two parts. The exam will consist of ~30 minutes of "describing" the fundamental concepts from core competencies (chosen from among 8 mechanical, electrical, and business cores) and, at a different time ~45 minutes applying the concepts in solving open-ended problems.	500

Figure 3: Point allocation for the one-credit Seminar course. Professional development learning is also included in the 1 credit Professionalism course. Both courses are taken every semester in students' 3rd and 4th years.

environment of discussion; a two-way dialogue that results in high-levels of learner engagement and participation. For the learner, SDL delivers knowledge content "just-in-time." This is a significant departure from traditional education methodologies that deliver a "supply" of knowledge that may or may not be applicable by the learner at the time of delivery. SDL seeks to improve comprehension, retention and skills mastery through the near immediate application of what is learned.

Technical content is delivered via "learning conversations" (LC), which are facilitated by the faculty members. A one-credit competency meets seven times, two hours each, over the course of half a semester. Prior to Spring, 2019, LCs occurred twice a week for an hour each. The change to two-hour LCs is expected to be more effective by allowing more time for learning activities, field trips, etc. LCs are generally flipped classroom style and are generally interactive, rather than lecture-based. For each hour in a learning conversation, students generally spend two additional hours outside of the meeting. By the end of a semester, students will have spent 40 hours on the competency, which is the requirement to earn one technical credit. Teachers scaffold the students' self-directed learning. A basic outline of a learning conversation is 10 minutes of Q & A, 60 minutes of learning or retention activities, and 30 minutes of new information. The last 10 minutes is for the instructor to give students an overview of next steps. Faculty have autonomy to alter this general guidance.

Solving problems in pairs at the white boards, doing experiments, doing Kahoot [14] quizzes, and verbally describing fundamental principles to each other are examples of common learning/retention practices. Assignments are turned in online and instructors are expected to provide feedback on student work quickly, within a day or two.

A recent change is using Google classroom to hold learning resources and to send/receive assignments for the 20 core competencies. This makes it easier for students on co-op placement to continue learning with their peers. Also, faculty have started using Apple i-pad Pros to efficiently write feedback on student work using the Apple pencil. Giving feedback to students quickly is one of the primary roles of both faculty and facilitators in this program.

Active, integrated learning includes a range of activities from field trips, conference presentations, peer to peer teaching, workshops and trainings in the fabrication lab and electronics lab, STEM outreach events, as well as workshops on professional expectations. Online gamification resources such as Kahoot [14], Quizlet [15], and Plickers [16] are regularly used. In Design, students email and meet with clients, vendors, and subject matter experts. Teams travel to industry client locations in a program-provided vehicle.

Written reflections continue the learning process. To facilitate the students' development of becoming excellent reflective learners, they are required to write three reflections per week in Seminar class. Two of the reflection topics are provided and one topic is of the student's choice. Provided topics include reflecting on the Jobs Package and Interview night, thoughts on a recent program event, ethical and leadership topics, and progress updates on learning goals. Facilitators grade student reflections weekly for Design, and professors grade the Competency Learning Journals. Reflection entries are also required in technical courses, so students write approximately 100 reflections each semester.

Game-based learning

Faculty in the program have increased the use of gamification and game-based learning in the past two years. In addition to online gamification apps such as Kahoot, Quizlet, and Plickers, game-like activities such as quizzing with the Immediate Feedback Assessment Technique (IF-AT) [17] cards and Jeopardy are used. Stand-alone learning games based upon Karl Kapp's gamification elements [18] and Gee's [19] principles of effective learning games are being developed. Students developing games to learn engineering technical content can be effective in gaining a deep understanding of new knowledge. Collis & Moonen [20] suggest that a process of learning in which the learners act as co-creators of learning resources is effective; these resources can then contribute to learning by others (peers). They call this Contributing Student Pedagogy (CSP). This follows Treveylan's [9] suggestion that students learn by helping others learn. IRE faculty recently started involving students in developing a variety of learning games. Two board games have been developed by students - ”The Game of Life with Six Sigma” which includes a purchased game board but uses student-developed cards to advance through the game. Student engineers also developed an original game called ”LiFE” to practice the fundamental principles of engineering. It is a board game played on a map of the local geography, and players move their game pieces along the Iron Range taconite mining region, advancing as they correctly answer multiple choice questions. In addition, students have planned and carried out two-hour ”Escape Room” learning events, which culminate with the two winning teams facing off in a game of Jeopardy on the college theatre stage. Details can be found in the 2018 ASEE paper by Leung and Pluskwik [6]. While a strict research protocol has not been developed to assess changes in learning under these active review methods, most, but not all, students enjoy the events and find them a valuable way to review content before the exam. Faculty appreciate the activities as additional ways for learners to practice retrieval of knowledge for long-term retention. It's better than ordinary studying. Data on the Escape Room events follows next.

Active learning event data

Data was collected from learners via written surveys just before and immediately after recent Escape Room events to practice retrieval of fundamental principles. Informed consent was obtained.

For the Escape Room data collected during the 2017-2018 academic year, there was a small increase (4.6 percent) in a student's fundamental principle exam score if they participated in the Escape Room event both semesters. Students' confidence levels were also noted by the ”check-in” faculty member, who asked each student how confident they were in describing the fundamental principles of engineering, both before and immediately after the Escape Room activity. Overall, 44 percent of students self-reported higher levels of confidence after the Escape Room activity. Student feedback on these activities during the 2017-2018 academic year included:

- ”Awesome way to study before exams”
- ”Exciting game with in-depth test on knowledge”
- ”Reminded me of principles I don't know yet”
- ”New, different, put a little pressure on us. I have further identified & verified strengths vs. weaknesses. Nice job, faculty.”
- ”Made learning fun, exciting, and highly competitive. Makes you think on your feet. Highly focused. Would be fun to try again.”
- ”Engaging and challenging. Feedback was key and present. More feedback when people get things wrong.”
- ”Fun way to start studying for fundamental principles. I don't know if I learned anything new but I was able to recall.”
- ”Allowed me to practice interleaved spaced retrieval.”

In Spring, 2019, three students developed a new Escape Room event. Written surveys completed by Escape Room participants after the event provided the following data:

Question 1: After completing the activity, how prepared do you feel you are for the Fundamental Principles exam? (1 = Not Prepared at all; 2 = Minimally prepared; 3 = blank; 4 = Somewhat prepared; 5 = Very prepared)

Preparedness level	**Mean**	**n**
BEFORE event	2.93	22
AFTER event	3.46	13
Change	Increase of .53	

Table 1: Students self-reported ’Preparedness for the exam” increased by 18%.

Question 2: What was the learning value of the activity compared to your ”regular” review activities? (1 = No learning value and didn’t help me; 2 = Minimally helped me; 3 = Didn’t impact my learning; 4 = Somewhat helped; 5 = High learning value and really helped)

Mean	**n**
4.04	13

Table 2: Students self-reported Value of activity compared to regular review activities as ”Somewhat helped”.

Question 3: Did you enjoy the activity? (1 = No I did not enjoy; 5 = Yes I enjoyed it a lot)

Mean	**n**
4.00	13

Table 3: Students self-reported ”Enjoyment of activity” as ”Fairly enjoyable”.

One student’s written reflection: “I think it would be fun to have stations that you cannot leave until you have correctly done a certain amount of fundamental principle describe sheets. This would add more of a competitive element that may engage the students more.”

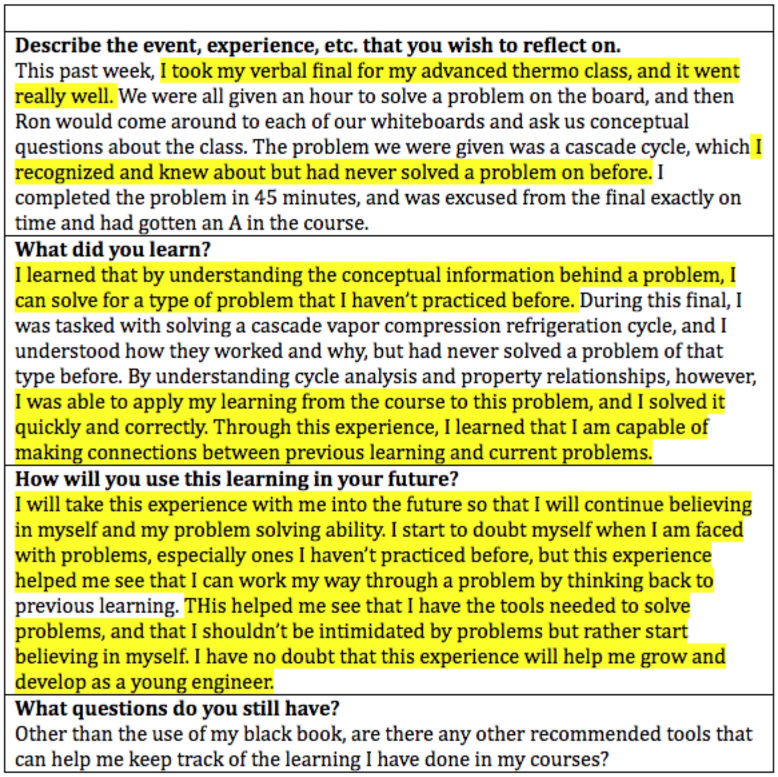
Another student wrote: “I believe this game was one of the most fun things I have done with fundamental principles. Therefore, I don’t know if I would want to change it or not. I believe what made it fun was that we were on teams and also the teachers were a part of it by dressing up to display the new FP challenge room.

Assessment of Learning and Student Reflections

An aspect of this program that is different than many others is that all exams are verbal. Learners complete four different types of verbal exams each semester: technical competency exams, Fundamental Principles Exam, Creative Innovative Open-ended Problem-solving (CIOPS) exam, and the Team Technical Exam. Some exams involve one learner speaking to a professor or a panel of evaluators. Other exams are done by a team of learners to a panel. An individual learner in this program completes 11 verbal exams per semester: eight technical credit exams, one fundamental principles exam, one open-ended problem-solving exam, one team technical exam, in addition to three design reviews. The evaluations done by panels of faculty and facilitators are thoughtfully planned and practiced to try to achieve consistency in feedback and grading. Generally, all evaluators attend an initial exam with a high-achieving student or team, then they discuss their subjective evaluation, to achieve some degree of calibration across all graders. Rubrics are used and revised yearly. A summary of exams and student reflections are presented next.

Technical competency exams

Technical competency exams are generally one learner assessed by the professor and last 30 - 60 minutes. The exam generally has the learner describe the basic principles or concepts of the course, solve one or more problems on a white board, and discuss the deep learning activity. Reflection questions such as "How does this learning connect to your other engineering knowledge?" and "How does this help you to add value in solving engineering problems?" are common in verbal exams. Students write Learning Journals to reflect in each competency.



Describe the event, experience, etc. that you wish to reflect on.

This past week, I took my verbal final for my advanced thermo class, and it went really well. We were all given an hour to solve a problem on the board, and then Ron would come around to each of our whiteboards and ask us conceptual questions about the class. The problem we were given was a cascade cycle, which I recognized and knew about but had never solved a problem on before. I completed the problem in 45 minutes, and was excused from the final exactly on time and had gotten an A in the course.

What did you learn?

I learned that by understanding the conceptual information behind a problem, I can solve for a type of problem that I haven't practiced before. During this final, I was tasked with solving a cascade vapor compression refrigeration cycle, and I understood how they worked and why, but had never solved a problem of that type before. By understanding cycle analysis and property relationships, however, I was able to apply my learning from the course to this problem, and I solved it quickly and correctly. Through this experience, I learned that I am capable of making connections between previous learning and current problems.

How will you use this learning in your future?

I will take this experience with me into the future so that I will continue believing in myself and my problem solving ability. I start to doubt myself when I am faced with problems, especially ones I haven't practiced before, but this experience helped me see that I can work my way through a problem by thinking back to previous learning. THis helped me see that I have the tools needed to solve problems, and that I shouldn't be intimidated by problems but rather start believing in myself. I have no doubt that this experience will help me grow and develop as a young engineer.

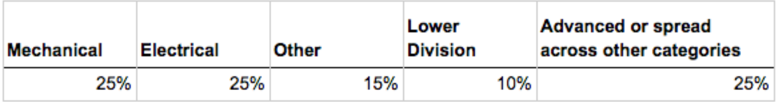
What questions do you still have?

Other than the use of my black book, are there any other recommended tools that can help me keep track of the learning I have done in my courses?

Figure 4: Student reflection after a recent technical competency verbal exam written by a female 3rd year engineering student, first year in upper division IRE program.

Fundamental Principles Exam

Students complete a verbal Fundamental Principles exam to a panel of faculty each semester. In the fundamental principles exam, students stand at a whiteboard in front of a panel and communicate their knowledge of the fundamental principles they have acquired from all of their technical competencies, including some from 1st and 2nd year pre-engineering courses. For each exam, the students select the principles they will be tested on, as follows: First semester juniors are required to have 18 principles on their list, second semester juniors - 22, first semester seniors - 32, and second semester seniors - 42. The program is moving towards testing on 100 percent of the fundamental principles from each technical competency that each student has taken; this is being implemented over a few semesters, and is based on the idea that frequent interspaced retrieval will push the “forgetting curve” [13] further into the future. The exam each semester motivates students to continue to review those principles as they progress towards graduation and beyond. No specific reflection is requested on this exam.



Mechanical	Electrical	Other	Lower Division	Advanced or spread across other categories
25%	25%	15%	10%	25%

Figure 5: Minimums from each disciplinary category for the Fundamental Principle Exam. Students take this exam in front of a panel each semester in their 3rd and 4th years.[3]

Design Exam

A new exam called the Project Technical Content Verbal Exam is being piloted in Spring, 2019. In this exam, project team members are asked to explain technical content for the project that another team member was primarily responsible for. In this way, team members are teaching each other, as Treveylan recommends [9]. For example, Bob has learned advanced heat transfer concepts for the team’s project for a local power generation company. Team members Jill and Kathy and Mike could be asked to explain how advanced heat transfer knowledge contributed to the team’s project calculations. A team score is given based on their ability to explain the technical aspects of their project solution. This is expected to increase peer teaching and knowledge transfer between team members.

Creative, Innovative Open-Ended Problem Solving Exam (CIOPS)

The CIOPS exam includes solving an open-ended problem, which is given approximately one day before the exam. In 8 - 10 hours, students go through a design process that they develop themselves and come up with multiple solutions for the problem. These exams are presented in front of a panel which consists of faculty, facilitators, and industry professionals.

Learner Reflection #1 - Male learner, end of 4th year, reflection on his CIOPS exam, in which he spent 8.7 hours (per his CIOPS timeline) and received a grade of A on his final CIOPS exam:

> Q: What step in solving an open-ended problem is your strength?
> A: I would say that the parts that include design are my strengths. These are pertaining to the design conception, design selection, and design evaluation. The reason I am strongest in these areas are do (sic) to my organization skills when using

> idea selection techniques as well as having a clear explanation during my design evaluation. I think I am very good at conceptualizing multiple solutions and determining the best solution to move forward with, then analyzing that solution.
>
> Q: What step in solving an open-ended problem do you feel you need to improve the most?
> A: The area I could use some improvement in is better identifying what is considered a requirement versus a constraint and why they are classified accordingly. I don't think that I do this badly, but I think that different people have different views on these. I think this needs to be more standardized, since different instructors seem to tell me different things.
>
> Q: How will you use this learning in your future?
> A: Although I will no longer have CIOPS exams, as an engineer, I will be able to use the skills and strategies I illustrated in this problem and build them into my process for solving real life engineering problems for my organization. I got great feedback on what I did well along with feedback for areas of improvement. I will be able to use this feedback and remember what I did well on to carry with me, and . . . to improve upon future open-ended problems."

Learner Reflection #2 - female learner, first semester in the program, who received a B- on her first CIOPS exam:

> Q: How you evaluate the effectiveness of your open-ended problem solving process?
> A: Throughout my design process, I feel like I may have spent too much time in my research phase. I think that I could have spent a lot more time trying to be creative with my solution. I also feel as though I could have spent more time trying to relate my problem solution to Thermodynamics and use more equations and formulas to backup my knowledge.
>
> Q: What is your Action Plan for continuous improvement?
> A: Next time I take the CIOPS exam, I plan to monitor my learning. I would like to keep track of how much time I am spending in each portion of the design process. This will help me to regulate my learning, and it will also help me stay on task.
>
> Q: How will you use the experience to continually improve your abilities as an engineer?
> A: One thing that I've learned this year is that learning from failure is important to your success not only as a student but in the workplace as well. If you don't learn from your mistakes you will never be able to succeed. I feel like I have failed my CIOPS exam. I know that I could have done much better. Even though I feel like I may have failed, I have learned a lot about myself as an engineer and areas that need to be improved upon before I become the engineer that I want to be. This experience will help me identify my weakest areas so I can set goals for my future CIOPS exams and for my future as an engineer.

Student engineers repeat the CIOPS exam process four times, each semester in their 3rd and 4th years in the program. Students' ability to define a problem, design and present solutions, both verbally in a presentation and with slides and handouts, in one day, develops markedly over the two years; the improvements are impressive.

Results from recent external validation of career-readiness

A satisfaction study to gain external validation on professional competence from employers and graduates was conducted by Johnson & Ulseth in 2015 [8]. At that time, there were 75 graduates of the IRE program. All were emailed a request to complete the survey and ask their supervisor to complete a copy of the same survey. Thirty graduates took the survey (40% completion) and 18 supervisors took the survey (24% completion). The survey asked respondents to rate all new engineers in the company who were non-PBL graduates on a 7-point Likert scale and then to rate the IRE PBL graduates on the same scale. Questions related to communicating effectively, acting professionally, ability to design system to meet needs with constraints, engaging in entrepreneurial thinking, ability to use modern engineering tools, ability to solve engineering problems, ability to function well on teams, efficient learner, ability to lead and manage people, and ability to lead and manage projects. The results from graduates and supervisors both indicated that the IRE PBL graduates perform better than their non-PBL peers in their first few years in the workforce. (See Figure 6.)

For example, on all ten of the graduate survey questions and in nine out of the ten employer survey questions, the mean score for the PBL graduates was higher than the non-PBL graduates. Employers reported the greatest difference between PBL and non-PBL graduates in “performing on teams,” “lead and manage projects,” and “being professionally responsible” [8].

That study reported employer comments:

> ”I would say on average the students from IRE that we have hired have been more mature and have further progressed along the development curve to be effective in real world industry.”
> Employer

> ”By a wide margin, I prefer working with the IRE graduates because they are so professional.”
> Employer

See the Johnson & Ulseth paper [8] for the full report.

As of January 2019, 160 engineers have completed the IRE program; these graduates were invited to a Leadership Conference in Minnesota. Eighty (50%) responded they would participate and 75 graduates took part in the 1-day workshop-style conference in January, 2019. The group shared their experiences from the early years of their engineering careers and were asked how their education at IRE contributed to their engineering experiences at work. Responses were strongly positive, and professional skills, job-search skills, and self-directed learning abilities were highlighted as strengths gained from the program.

	Average Score (from 7-point Likert Scale)		
	Non-PBL Graduate	PBL Graduate	Delta: PBL - Non-PBL
Communicate Effectively	4.4	4.9	0.6
Professionally Responsible	4.6	5.2	0.6
Design Systems	4.8	5.0	0.2
Entrepreneurial Thinking	4.1	4.6	0.5
Modern Tools Use	4.6	4.6	0.0
Solve Engineering Problems	4.4	4.8	0.4
Perform on Teams	4.3	5.3	0.9
Efficient Learner	4.4	5.0	0.6
Lead and Manage People	4.2	4.4	0.3
Lead and Manage Projects	4.3	5.1	0.8

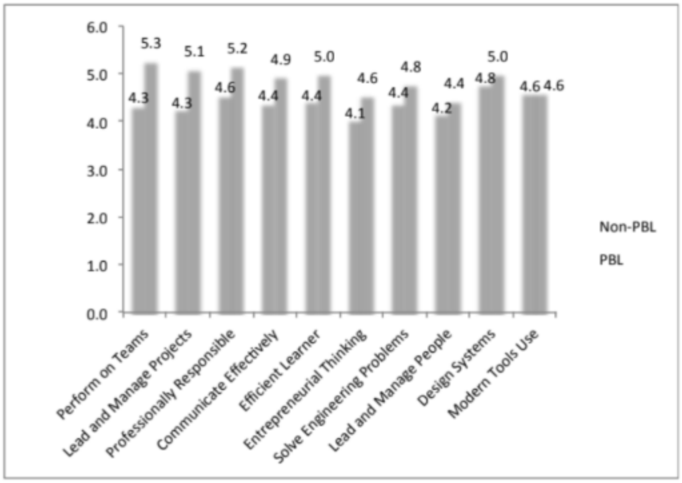


Figure 6: Supervisor survey results show that graduates from this PBL program score higher than non-PBL graduates in 9 of the 10 questions asked of supervisors ($N = 18$).[8]

Model of continuous improvement

The IRE program will continue to change. Every semesters, suggestions from learners, faculty, advisory boards, learning science research, and colleagues are inputs to continuous improvement. Two faculty summits are held every semester to review and improve learning practices. In fact, a program goal is to change by 15 - 20% each year, based on input from these stakeholders. Program faculty use a scholarship of teaching and learning philosophy and seek to make evidenced-based change in a model of continuous improvement. The rapid pace of change can be a challenge for faculty and students alike.

Challenges

Faculty in this program, like students, need to have a growth mindset and be adaptable, flexible, self-directed learners, and strong team players. Faculty, both new and experienced, have found the high level of expectations to be challenging. The program includes many events each semester that faculty are expected to attend and to give feedback/evaluate, including TED-like talks by every student every semester, Engineering Career Fair and Live Interview Night (as well as reviewing student resumes, cover letters, and conducting mock phone interviews), an Ethics conference, helping with various group learning events, such as the Escape Room described earlier, assessing design teams by serving on Design Review panels, assessing student learning in the Fundamental Principles Exam and CIOPS Exam for students each semester, and more. These are all in addition to regular course instruction and grading (the program has no graduate or teaching assistants) and is also in addition to the promotion and tenure requirements of the university. The program changes quickly, moves at a fast pace, and requires a high level of teamwork and communication. The use of many varied technologies is required, so faculty must engage in self-directed learning as much as the students do. For example, making mini lecture videos, using the i-pad, and moving to new online learning management systems are changes made in the last year. Much of this knowledge is tacit ("we just know") or experimental ("we'll try it"), and this is challenging for faculty.

In addition, faculty members each facilitate a project team each semester, which involves managing student design learning with an external client in an industry that the faculty member may not be familiar with. For example, the author has facilitated student teams working on design projects in an electrical power plant, an aircraft manufacturer, a taconite mine processing plant, an aquaponics research station, and more. Faculty may be asked to facilitate student learning in advanced competencies in topic areas that are outside the "normal" courses offered each semester. These advanced credits stem from learning required by the student team to complete the design project or in the students' interest area. The facilitator or faculty member assists the student in seeking appropriate resources, overseeing their process of learning and documentation of that learning, and application of the topic to the industry project. Validation comes from the client or other subject-matter expert. For completing such work successfully, the student receives a grade for 1 credit per advanced competency. Some faculty may feel challenged by these expectations, most of which ask for participation beyond that normally found in more traditional programs.

Replication

Can this program be replicated successfully? Yes, with much support and local adaptations. This program has been replicated in the Minneapolis area of Minnesota with some modifications due to its partnering community colleges and local companies. Even in this sister program, Twin Cities Engineering, which is in the same Integrated Engineering department and carries out the same curriculum, there are differences in culture and projects. The key internal ingredients for success include a willingness of faculty to adapt pedagogy in light of best practices from learning science, a growth mindset, a positive, supportive culture, and a strong academic leader. University support such as the registrar, financial aid, and the Dean's office is imperative, because 1-credit courses and PBL projects do not fit well within many existing systems of record-keeping at educational institutions.

Dr. John Heywood suggests that "every teacher has to be a researcher in order to find out which theories work for them in the classroom and which do not" [21]. This scholarly reflection and willingness to continuously improve is crucial in a program like this.

External resources that help tremendously are strong partnerships with local industry and perhaps additional funding streams for dedicated project rooms, labs, and large-group meeting spaces. PBL requires a low student-faculty ratio, and faculty compensation is the largest expense. A strong educational leader with an innovative, entrepreneurial mindset is needed, as is a faculty group that act as a team and supports one another and the learners with a growth mindset and willingness to cooperate and learn together. The freedom to try and perhaps to fail, then try again, is required.

Conclusion

This engineering education program is based on learning science research and application of new knowledge in the field of engineering. The program is intensive, highly personalized, and flexible. Students and faculty must have a growth mindset to be successful. The results are highly skilled graduates with the ability to solve technical problems, communicate effectively, work in interdisciplinary teams, and self-direct their own learning in order to add value in a complex, rapidly changing society. This paper described the design and open-ended problem solving learning activities and assessments, as well as some details on how technical knowledge is learned through game-based activities. The program embraces continuous improvement and faculty are encouraged to try evidenced-based learning processes, to measure the results, and to improve as needed. The attention to quality of learner outcomes is of the utmost importance in this program, and employers verify that the graduates are highly technical and highly skilled as they enter the workforce. Future plans include more student involvement in game-based learning and development of learning games, using more online delivery methods, increasing the co-op experience to two or more semesters, and better tracking individual progress through their reflections. Aspects of the program are adaptable for other universities. Additional resources would likely be needed for PBL facilitators and project team rooms. Strong industry support to garner engineering expertise for design panels is helpful. A culture of student-centered, supportive facilitation in learning as well as a growth mindset is needed by participants. Individual elements such as adding more student reflections to coursework, using online gamification, and including retention activities for prior learning are more easily integratable into existing programs without additional cost.

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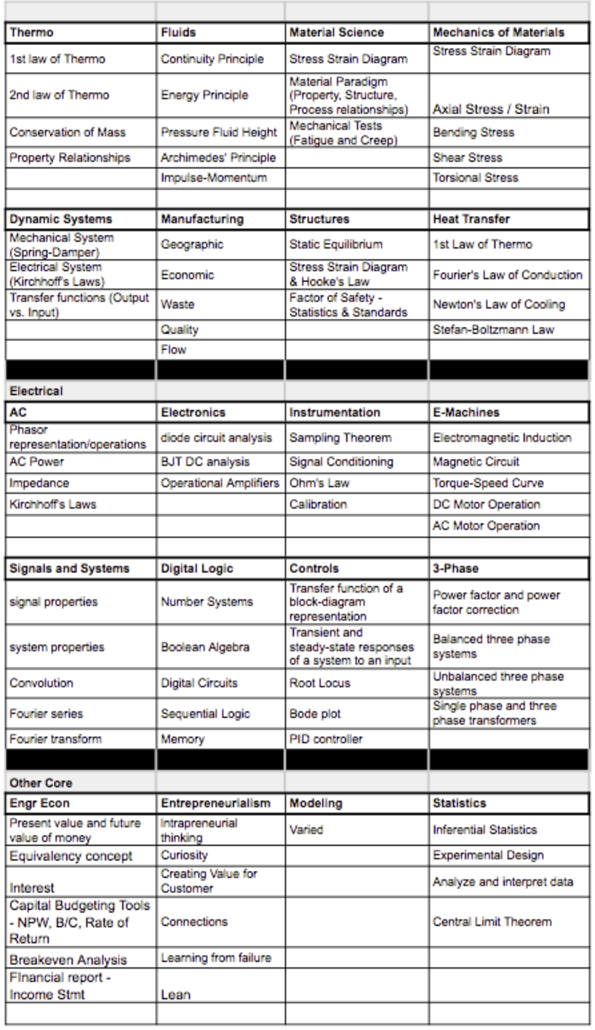
Appendix A: Iron Range Engineering Fundamental Principles as of Jan 2019



Thermo	**Fluids**	**Material Science**	**Mechanics of Materials**
1st law of Thermo	Continuity Principle	Stress Strain Diagram	Stress Strain Diagram
2nd law of Thermo	Energy Principle	Material Paradigm (Property, Structure, Process relationships)	Axial Stress / Strain
Conservation of Mass	Pressure Fluid Height	Mechanical Tests (Fatigue and Creep)	Bending Stress
Property Relationships	Archimedes' Principle		Shear Stress
	Impulse-Momentum		Torsional Stress
Dynamic Systems	**Manufacturing**	**Structures**	**Heat Transfer**
Mechanical System (Spring-Damper)	Geographic	Static Equilibrium	1st Law of Thermo
Electrical System (Kirchhoff's Laws)	Economic	Stress Strain Diagram & Hooke's Law	Fourier's Law of Conduction
Transfer functions (Output vs. Input)	Waste	Factor of Safety - Statistics & Standards	Newton's Law of Cooling
	Quality		Stefan-Boltzmann Law
	Flow		
Electrical			
AC	**Electronics**	**Instrumentation**	**E-Machines**
Phasor representation/operations	diode circuit analysis	Sampling Theorem	Electromagnetic Induction
AC Power	BJT DC analysis	Signal Conditioning	Magnetic Circuit
Impedance	Operational Amplifiers	Ohm's Law	Torque-Speed Curve
Kirchhoff's Laws		Calibration	DC Motor Operation
			AC Motor Operation
Signals and Systems	**Digital Logic**	**Controls**	**3-Phase**
signal properties	Number Systems	Transfer function of a block-diagram representation	Power factor and power factor correction
system properties	Boolean Algebra	Transient and steady-state responses of a system to an input	Balanced three phase systems
Convolution	Digital Circuits	Root Locus	Unbalanced three phase systems
Fourier series	Sequential Logic	Bode plot	Single phase and three phase transformers
Fourier transform	Memory	PID controller	
Other Core			
Engr Econ	**Entrepreneurialism**	**Modeling**	**Statistics**
Present value and future value of money	Intrapreneurial thinking	Varied	Inferential Statistics
Equivalency concept	Curiosity		Experimental Design
Interest	Creating Value for Customer		Analyze and interpret data
Capital Budgeting Tools - NPW, B/C, Rate of Return	Connections		Central Limit Theorem
Breakeven Analysis	Learning from failure		
FInancial report - Income Stmt	Lean		