A New Model of Project Based Learning

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Abstract
A new model for engineering education has been developed and funded. The model is 100% project based learning (PBL) where the students develop their own learning objectives. The projects are authentic needs contributed by collaborating industries. Students monitor the acquisition of 32 technical competencies and all of the design and professionalism competencies required of new practicing engineers. The reasons for the new model, description of the model, research supporting the model, methods for evaluating the model and its transportability are discussed.

Factors that Motivated the Development of the Model
Educating Engineers: Designing for the Future of the Field[1] together with other recent research and reports on engineering education, make a compelling case for envisioning engineering education in a new way. Calls have come from the National Academy of Engineering, National Science Board, industry leaders, engineering education leaders, and others for a new model that will produce engineers who will meet the challenges of today and tomorrow to keep the United States competitive in an increasingly competitive global economy. This same call is made with the statement that the current model for engineering education will not meet the needs of tomorrow and that change has always been part of engineering education as it has risen to new challenges[2]. Despite these calls, which have resonated throughout engineering education, there seems to be little movement towards change in mainstream engineering education. The developers of this new program were given the unique opportunity to design and implement a model aimed at meeting these calls for improvement.

History
The prime movers for the development of this model are engineering faculty who were dissatisfied with the response of academia to the calls for change in engineering education. They saw barriers to change being rooted in the department and college cultures. With this design constraint, they sought to create, from scratch, a new private institution where they would be unconstrained by legacy policies and non-believers. For five years, 2003 to 2008, they met to design a new model and seek funding. Unfortunately, inquiries to funding agencies, both governmental and private, were fruitless. The organizing group was running out of momentum when a publicly funded opportunity arose.

In northeastern Minnesota there is an ore deposit mined by several mining companies. A regional governing agency is tasked with planning for and allocating the tax imposed on the mining companies for each ton of ore removed from the earth. In response to regional industry's need for a more educated workforce and in an effort to create economic development, the agency partnered with the organizers of this model and two public higher education institutions, a community college consortium and an ABET accredited state university to establish a new project based engineering curriculum. A curriculum whose educational objectives include preparing an engineer with the professional and technical skills needed to "create, develop, lead, and manage in a wide range of enterprises that result in sustainable and enhanced economic regional development through their disciplinary expertise."[3]

The agency is funding the program at approximately $1 million per year to educate entering cohorts of 25 students through the two year experience. Graduating engineers from the program are expected to have experiences that would provide them with the expertise to serve the industries of the region, contribute as entrepreneurs in the region, or leave the region and serve society in any of the capacities expected of engineers graduating at the nation's colleges.

Minnesota State University Mankato and Itasca Community College are the institutions of higher education that have collaborated to develop and offer the Iron Range Engineering (IRE) program. Instructors at IRE are faculty members at Mankato and Itasca. The leadership of both institutions have paved the way for the program to begin.

Description of IRE Model

The Iron Range Engineering program is upper division, *team oriented* project based learning focused on *industry-contributed and industry-mentored design projects.* An *innovative* aspect of the program model is that student learning activities (both technical and professional) are centered around design projects offered by external organizations. While working on the projects, students have ownership in the selection of their competencies and in the design of learning objectives as well as learning activities.

Students enter IRE after completing their lower division math, science, and engineering requirements. They are typically graduates of community colleges. Upper division curricula consist of four 15-credit semesters. Each semester, students complete **8 technical credits** and **7 professional and design credits**; however, there are no formal courses, in the sense that each course would have a different schedule of weekly meetings and that faculty members are assigned to teach separate courses.

IRE students earn a Bachelors of Science in Engineering (BSE). Of the 32 technical credits, there are 8 mechanical core credits and 8 electrical core credits in which all students gain proficiency. For each of these 16 core technical credits (each referred to as a competency), students develop “personal models” to develop conceptual understanding of the basic fundamentals and general principles across the domain of the competency. Then, they undertake more in-depth learning activities intended to develop expertise in a more focused area of their choosing within the competency. Roughly 70% of the time, these in-depth learning activities occur within the context of their industry-contributed, industry-mentored project. This is how IRE applies project based learning (PBL) to its approach to teaching.

In cases when the technical learning cannot be in the context of the project, another deep learning activity is chosen and executed. Typical activities include: (a) design or execution of Model Eliciting Activities (MEA); (b) student designed, conducted, and analyzed experiments; or (c) construction of an advanced computer program, e.g., expert system or simulation program.

The remaining 16 technical credits are advanced topics beyond the core that address student interests or needs. If a student completes 12 credits in any area they can earn an "emphasis". Typical emphases areas are mechanical systems, thermal fluid systems, electrical systems, or biomedical. When a student selects an advanced or technical elective, their first task is to create the syllabus, which includes learning outcomes and objectives, learning activities, assessments, deliverables, and grading criteria. The completion of the syllabus is iterative processes with the faculty helping the student verify appropriate content and scope. The faculty sign final approval of the syllabus at the beginning of the learning process, acting as a contract for the semester's learning.

In addition to the technical credits, each semester students can earn up to 7 credits for documented development in professional and design competencies. The specific competency areas are: design process, design deliverable, design communication, leadership and management, learning about learning, teamwork, communication, professional responsibility, and personal responsibility. Embedded in these competencies are ABET student outcomes a-k plus two additional program specific outcomes in leadership/management and entrepreneurship. IRE faculty members create a new syllabus for the professionalism competencies each semester to provide for a wide variety of learning activities across the four-semester curriculum.

Student experience in a semester is as follows:

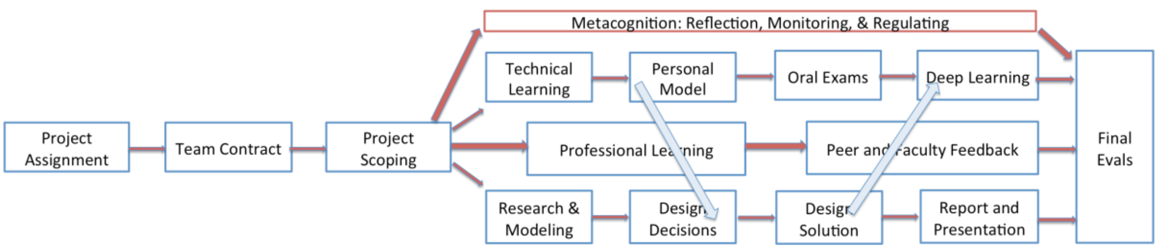

Figure 1. Block diagram of semester learning experience for IRE students.

- Prior to the semester new project descriptions are made available to the students. They select preferences based on personal interest and management of their overall technical competency needs. Project assignments are made to best meet the needs of the student, the client, and the other students in the program.
- On the first day of the semester students assemble with their new team. (Students are given the opportunity to rank their project preference – they usually get assigned to their first choice.) Teams vary in size from 3 to 10. The first order of business is the development of a team contract – a set of expectations and responsibilities that they believe are essential to the successful execution of their project.
- Within the next few days they meet with their industry client for a requirements capture and scoping process. As the students gain understanding of their project they select their 8 technical competencies for the semester – some from the core areas and some from the advanced and elective areas. The goal is to select as many as possible that have direct connection to the industry project.

- For the next seven weeks students dedicate a minimum of 6 hours per day to their learning to develop expertise with respect to the 8 technical competencies and 2-4 hours per day in the ideation, research, modeling, and experimentation phases of their project. The goal of the learning for each competency is to progress from identifying fundamental knowledge and general principles to the development of personal models (such as concept maps, structure maps, and analogies), to the practice of closed-ended fundamental of engineering type problems, to the starting of the execution of student designed deeper learning activities. Learning activities during these phases include “learning conversations” (daily scheduled 2 hour faculty led or student led active learning workshops), one on one faculty conversations, workshops by external experts such as practicing engineers, peer group learning, self guided research and learning, problem solving sessions, and reflection.

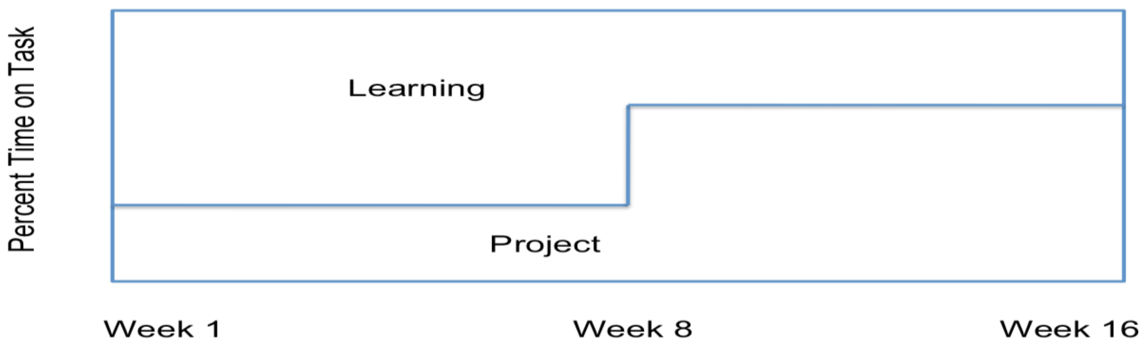

Figure 2. Approximate time on task for learning activities vs. project execution during semester.

- Upon reaching the completion of the personal model development, students stand for an oral exam where high levels of understanding of conceptual relationships are expected and evaluated for. Students perform written exams on the closed ended problems and submit extensive documentation for the deep learning activities as well as stand for a defense on the acquisition of the depth of knowledge.
- During daily team oriented project time students apply learned material to the project, complete weekly design reviews with faculty, meet often with clients, and prepare a research report, a modeling report, and the design plan for their experiment.
- At mid-semester there is a shift in balance of time. Most of the basic conceptual learning is completed and documented. In the last half of the semester up to 6 hours per day are spent on design project activities such as completion of their experiment, design option decision making, manufacturing of prototypes, testing, making design improvements, and design documentation. In the remaining 2-4 hours per day students are completing their technical learning. This is where much of the higher level contextual learning is taking place. They make connections between designs and their technical competencies and they complete their MEAs or other active deep learning activities. Daily learning conversations continue and are done at the request of the students as their new learning needs arise.

Metacognition plays a key role in these learning phases. Students identify their primary learning style(s) early in the IRE program and build strategies which make the most effective use for each learning style. Students reflect often on their selection of learning approaches as well as monitor the effectiveness of the approaches and regulate their learning by making changes in their approach. One fourth of the grade in every technical competency is based upon the students use, documentation, and oral description of their metacognition strategies and use.

Throughout the entire semester students are tracking their progress on development of professional competencies. Weekly, there are mini workshops on topics like learning, etiquette, writing, ethics, etc. Each semester students are given multiple opportunities to have feedback provided on their written work and speaking skills. They also practice giving effective feedback to other students. Each week a different practicing engineer from industry comes for lunch and "story hour" where she or he shares important messages and experiences from their careers.

At the end of the semester there are several culminating events:

- **Practice Final Design Review:** where students get faculty and peer feedback in a non-graded opportunity to give their design project presentation. After being given the opportunity to use the feedback for improvement the students present their final design work and summary of their learning in an interactive design review before an evaluative audience of their peers and faculty.
- **Client Design Review:** student teams present their designs to their clients for further evaluation. After client design reviews students turn their attention to final grading. Students upload all of the evidence of their technical and professional learning to the local server for evaluation and then archiving.
- **Defense:** students stand for defense of all learning both in sophistication and in quality of work. This is similar to an oral exam. All evidence is presented and faculty members question the students to verify extent of learning.

Faculty members evaluate sophistication using an adapted version of Bloom's revised taxonomy[4] where factual, conceptual, procedural, and metacognitive domains are analyzed along a continuum of cognition from low-level ,memorizing (1), to high level, evaluating and creating (5 & 6). Quality is evaluated on a 5-point Likert scale ranging from poor (1) to exceptional (5). To anchor this scale a 2 is representative of the quality that might earn a grade of C in a traditional upper division engineering course and 4 is representative of the quality of work one would expect from an acceptable entry-level engineer.

Knowledge Dimension								
	Metacognitive Knowledge							
	Process Knowledge							
	Conceptual Knowledge							
	Factual Knowledge							
		No Exposure (0)	Remember (1)	Understand (2)	Apply (3)	Analyze (4)	Evaluate (5)	Create (6)
	Cognitive Dimension ==>							

Figure 3. IRE adaptation of Bloom's revised taxonomy[4]

Students repeat this sequence for four semesters. Each semester, faculty remove scaffolding such as structure and focus in order to develop self reliance and confidence. In addition, higher levels of sophistication are demanded in all facets – technical learning, professional actions, metacognition, and design execution.

The first14 students started IRE in January 2010 (first generation) and will graduate in December 2011. A second generation (10 students) began in September 2010 and the third generation of students have applied and been accepted for September 2011 (25 students).

Research Supporting Program

The IRE Program builds on what is known about learning experiences that are most likely to lead to learning that contributes to the development towards expert levels of professional practice. Litzinger, Lattuca, Hadgraft and Newstetter[5] summarized the instructional practices that support such learning experiences; they divided those practices into three sets: affective, cognitive, and meta-cognitive.

Practices related in the affective category apply mostly to engaging and motivating students, because to learn in ways that support the development of expert professional practice students must be motivated to engage in "deliberate practice", that is practice with feedback performed with the intent of improving knowledge and/or skills[6]. Deliberate practice requires metacognitive skills because the students monitor their own learning, deciding if their present level of knowledge/skills is adequate and if not, they decide the best approach to improve their knowledge/skills.

Research has shown that explicit instruction on meta-cognitive processes is effective in helping students develop them[7]. Coutinho[8], along with Otero and Campanario[9], found that students with good metacognitive skills and strategies are more likely to achieve academic success and a high GPA. Students with poor metacognition may benefit from education to improve their metacognitive abilities and learning[10]. Schoenfeld[11] found about half of his calculus students in a large lecture class, when presented with an integral that could be done quickly with substitution, chose more difficult and time-consuming methods. They "demonstrated mastery of more difficult subject matter than did the ones who used the simple substitution," but ignored a strategic problem-solving rule: "Never use any difficult techniques before checking to see whether simple techniques will do the job"[11]. Selden et al.[12] found that over 75% of students in a differential equations course failed to solve non-routine calculus problems even though (i) instruments administered showed they demonstrated sufficient knowledge of calculus on routine problems and (ii) students in this study were among the most successful at the university measured by a variety of traditional indicators. The authors concluded these students, even with knowledge of calculus content, did not have "deep understanding and the ability to use this knowledge flexibly"[12]. Similar themes are echoed in a study by Weber[13] who showed "that undergraduates often are aware of and able to apply the facts required to prove a statement but still fail to prove it" because they lack strategic knowledge, "knowledge of how to choose which facts and theorems to apply", which he showed "doctoral students appeared to possess and undergraduates did not" [13]. The IRE focus on self-directed learning aligns very well with the need to have students attend to and develop their metacognitive skills.

Development of expertise also requires that students develop deep conceptual knowledge, key technical and professional skills, and the ability to apply their knowledge and skills to authentic engineering problems. To develop the ability to apply their knowledge to authentic problems, students must have multiple opportunities to develop this ability. Thus, having the IRE model of PBL integrated into each semester of the junior and senior year is well aligned with the need to provide multiple experiences with authentic problems.

Support for the Efficacy of Problem-based Learning

Problem-based learning has been in engineering programs for many years. However, few programs have integrated it extensively throughout the curriculum. Among the programs that have integrated PBL across the curriculum are Aalborg, Linkoping, Roskilde and Maastricht in Europe and Worcester Polytechnic University in the US. Recently several engineering programs in Australia, including civil engineering at Monash and University of Southern Queensland and chemical Engineering at RMIT Australia, Victoria University, and University of South Australia. The best documented example of PBL integrated across the curriculum is that at Aalborg University in Denmark[14,15].

Academic programs for engineers at Aalborg University have PBL integrated into each semester of study and typically accounts for 50% of a student's academic credits. De Graaff and Kolmos[14] note that PBL at Aalborg can be classified into three broad categories depending upon the extent to which the learning is directed by the supervisor or by the students. In the first two types of projects, "task" and "discipline", learning objectives are formulated in traditional ways. In a task-project the supervisor exercises considerable control over the learning process by selecting the subjects to be engaged as well as the expected modes of learning. In a discipline-project, the students have free choice of a problem within the subject area or a problem will be given and the students have free choice on the method of solution. The third type of project, a 'problem-project', the problem is ill-structured to the point that the students must select the subjects that they must engage in as well as the methods to be used.

The types of projects vary as the students go through their studies[15]. Task and problem-projects dominate the first year, task and discipline dominate the second and third years, and in the final years, problem-projects dominate. The learning objectives also vary across the years of study. In the first year, many objectives relate to building general project competence and methodological awareness needed to be successful in a PBL environment. In other years, the focus is on specific technical objectives. The Aalborg curriculum leads to substantial enhancements in the qualities of their graduates compared to those from a more traditional program, as evaluated by industry[16].

A comparison of classes of medical students graduating from both traditional and problem-based learning (PBL) curricula from 1993 to 2006 considered "undergraduate grade point averages, performance on the USMLE Step 1 and Step 2 exams, faculty contact hours, and residency directors' evaluations of [University of Missouri-Columbia School of Medicine (UMCSOM)] graduates' performance in the first year of residency"[17]. The study showed that mean "six of the ten comparisons for USMLE Step 1 and six of nine comparisons for USMLE Step 2 are significantly higher ($p < .01$) for UMCSOM PBL students than for first-time examinees nationally. These differences cannot be accounted for by pre-selection of academically advantaged students, increased time on task, or reduced class size"[17]. Further, the study concluded that the "PBL curricular changes implemented with the graduating class of 1997 resulted in higher performances on USMLEs and improved evaluations from residency program directors. These changes better prepare graduates with knowledge and skills needed to practice within a complex health care system"[17].

The VaNTH project[18] offers a quasi-experimental study to support improved student learning with respect to more challenging problems[19]. The POGIL project[20], which emphasizes a guided inquiry approach, has published at least two studies that provide evidence for improved student performance when compared to more traditional approaches[21,22]. A "systematic review of evidence of the effects that problem-based learning during medical school had on physician competencies after graduation" concluded that "[p]roblem-based learning during medical school has positive effects on physician competency after graduation, mainly in social and cognitive dimensions"[23]. A "qualitative meta-synthesis approach to compare and contrast the assumptions and findings of the meta-analytical research on the effectiveness of PBL" found that "PBL was superior when it comes to long-term retention, skill development and satisfaction of students and teachers, while traditional approaches were more effective for short-term retention as measured by standardized board exams"[24]. Studies of problem-based learning in medical school before 2006 tend to support the simplistic summary offered above [25,26]. Finally, Capon and Kuhn offer a quasi-experimental study that supports improvements in student learning when using problem-based learning[27]. In summary, evidence for situation-anchored approaches is strong, but not as compelling as the practice of organizing students in small groups. Furthermore, faculty members who apply scenario-based approaches very frequently organize their students in small groups; therefore, as Prince and Felder[28] have noted, it may be difficult to separate influences of using small groups from the influences of using situation-anchored approaches.

Assessment and Evaluation

The faculty have developed and implemented an assessment and evaluation program aimed at providing essential feedback to the program as it evolves and at measuring the success of the model in graduating engineers with the desired skills and attributes. Focus areas are cognitive development, technical knowledge acquisition, professional competency acquisition, and student interest and motivation.

The following tools are being used to establish a baseline and monitor growth from the beginning to the end of the students' upper division experience:

- Self Directed Learning Readiness Scale (SDLRS). This is an instrument for evaluating an individual’s perception of their skills and attitudes that are associated with self-directedness in learning. The scale is structured around eight factors, attitudinal and personality that are linked to self-directedness. Other than learners' perception of readiness for self-directed learning, this instrument is used for researching the relationship between self-directed readiness and other personality variables.[29]
- Study Process Questionnaire (SPQ). The SPQ, developed by Biggs, determines the relationship between students' study processes and the structural complexity of their learning. Study processes are conceived in terms of three independent dimensions: (i) utilizing, (ii) internalizing, and (iii) achieving. Each dimension has a cognitive (strategic) and an affective (motivational) component.[30]
- Motivated Strategies for Learning Questionnaire (MSLQ). The MSLQ has been used for assessing college students' motivational orientations and their use of different learning strategies. The MSLQ, based on a general cognitive view of motivation and learning strategies, contains two sections. The motivation section consists of 31 items that assess students' goals and value beliefs for a course. The learning strategies section includes 31 items regarding students' use of different cognitive and metacognitive strategies and 19 items concerning student management of different resources.[31]
- Transferable Integrated Design Engineering Education (TIDEE - recently renamed IDEALS). The IDEALS consortium developed an integrated system for assessing outcomes related to students' personal capacity, teamwork, design processes, and solution assets. Instruments are web-based and designed for formative and summative use.[32]
- ABET Outcome electronic portfolio analysis. This is used to evaluate student attainment of student outcomes in Criterion 3, i.e., a-k.
- National Survey of Student Engagement (NSSE), survey instrument intended to assess the extent to which engineering students are achieving certain learning outcomes desired of engineering graduates.[33]
- Concept Inventories (CI) are multiple-choice instruments narrowly focused on learner understanding of essential conceptual knowledge. These instruments provide a multitude of uses that range from diagnostic and formative purposes to guide instructional planning, to summative purposes for evaluating overall learning.[34]

- Full length practice Fundamentals of Engineering Exam (FE) practice exams from Professional Publication Inc. (PPI) are used as part of a mock FE exam to assess student attainment of technical knowledge.

Early Results

Two semesters have been completed. Students have executed 10 projects for industry clients. Feedback from the clients has been positive. *"…[I] Just attended the closeout presentation on the Filter Bag Wash system that was designed by six of your students. They did an **outstanding job**. The design, experiment, and validation were of higher quality than many efforts I've seen from paid engineering consultants. I am extremely impressed…Area Manager local iron mine".* Utilizing the Bloom's modified taxonomy as a guide, faculty have been able to track increases in sophistication of student learning of technical knowledge, depth of problem solving abilities, and ability to execute engineering design. The program received a state award for excellence in curriculum development. Three entrepreneurial projects were entered in a state-wide business competition. Two of the projects placed in the top 10 in their division with one of those earning finalist (top 3) designation. One student group participated in a nation-wide General Electric-sponsored Lean Engineering University Challenge were they designed and implemented a significant Lean process improvement in a GE manufacturing plant. This group placed second in the nation. Baseline measurements have been taken using all of the tousle described in assessment/evaluation. In-progress data is not yet available.

Model for Adaptation at Other Institutions

The IRE model of learning can be logistically implemented at a wide variety of institutions in a wide variety of engineering programs. Groups of (25-50) students operate in a project based format with a few lead faculty (4 at IRE). An important attribute of this model is the authenticity of the industry projects. Another important attribute is the existence of intense faculty student interactions that are unlike those in most engineering programs. Given these attributes, a cohort model would be possible in small departments or as a special program in larger departments. Many universities already employ similar cohort models in their honors programs. Aalborg University Denmark with a student population of over 14,000 has been implementing a very similar model of education for its entire student body for 35 years[35].

Beyond logistics, however, the model does have barriers. Adaptation of pedagogies not in wide use suggests that there would be resistance by university faculty to make the instructional shifts and give the ownership of learning choice to students. The IRE faculty members have faced significant criticism from university faculty claiming that the model is inferior and provides insufficient education. Evaluation panels on national grant programs have rejected the model. For example, "...students [will] have large gaps in their technical competencies. Moreover, the panel wonders if the graduates end up being more like technicians than engineers."

Future Work

In 2011 the first cohort of students will graduate and enter the workforce. Both a case study to capture the development story and a longitudinal study to analyze the impacts of the education on engineers as they enter the workforce are planned for imminent implementation. Faculty will continue the assessment and evaluation program to feed further development and to begin answering research questions about the impact of the model on student learning.

Summary

A new model of engineering education has been developed and implemented. The attributes of the model include: student ownership and management of technical competencies; a focus and equal importance put on the development of all professional attributes listed in ABET a-k plus leadership, management, and entrepreneurship; 100% project based learning with authentic and complex industry contributed and mentored team projects. Students have begun this upper-division program and will graduate in December 2011. An evaluation and assessment model has been developed and instituted. The results of the evaluation will be able to characterize the strengths and weaknesses of the graduates and will contribute to the knowledge about the usefulness of such a model and its potential for widespread adoption.

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