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SELF-DIRECTED LEARNING IN PBL

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AALBORG UNIVERSITY
DENMARK

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AALBORG UNIVERSITY
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Dissertation submitted

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CV

Ronald Ulseth is the lead developer and director of the innovative new Iron Range Engineering pedagogical model. Ulseth was recognized by Minnesota Governor Mark Dayton at his 2012 State of the State address for this innovation. He was also presented the Rural Community College Association Innovator of the Year, the Labovitz Entrepreneurialism Award for Innovative Leadership in Education, and the Progress Minnesota awards for success. He lobbied for, acquired, and oversaw design and construction of a new learning facility for Iron Range Engineering. He develops and nurtures relationships across all levels of K-12, higher education, government, and industry. Ulseth has presented the IRE model at regional, national, and international engineering education conferences.

Starting with 10 students at each college (Hibbing Community College and Itasca Community College), he worked with Aaron Wenger to build both programs to 60 engineering students. In 1999, Ulseth took over from Wenger as sole leader at Itasca Community College and developed the program into national prominence with an enrollment of over 150 students.

Ulseth is a retired Commander in U.S. Navy Reserve. He served as the commanding officer of five naval units. Highest position held: Director, Navy Reserve Customer Service Directorate 2005-2007. Ulseth acquired certification as an Engineering Duty Officer and worked as an engineering officer in navy shipyards across the nation and the world.

ENGLISH SUMMARY

Engineering education is at a crossroads. The desired attributes of the engineer of the future go beyond the strong analytical skills desired of engineers in the past. Future engineers must be creative, ingenious, and flexible. They must possess great skill as communicators and professionals. Above all, they must be accomplished, self-directed learners. Engineering education of the past provided explicit opportunities for students to develop strong analytical skills, but only implicit or worse, tacit, learning of these other important attributes. For our future engineers to develop high levels of skill and accomplishment, the days of engineering students having the majority of their time spent in lecture halls and doing closed-ended homework problems have to become a part of the past. If we want students to acquire complex skills, they need to spend much time practicing those skills and receiving ample formative feedback on their development.

Project-based learning (PBL) is a pedagogy perfectly aligned with the developmental trajectory of an engineering student. In PBL, students work on teams applying engineering design processes to complex, open-ended problems. They develop interpersonal skills, conflict management strategies, and professional responsibility. They write technical engineering documents and give professional engineering presentations. Their motivations to learn become greater as they are given autonomy, realistic challenges, and opportunities to become connected to each other and their profession. They gain identity as emerging engineers. Most importantly, they take on the responsibility of managing their own learning of technical knowledge. They learn how to learn. They become self-regulated, metacognitive, self-directed learners. As a result, engineers who graduate from PBL curricula are more ready to enter engineering practice and look more like the desired engineer of the future.

PBL engineering educations have been available to students in Europe for more than 40 years. In Denmark, the PBL engineering universities are renowned for graduating students with these skills and attributes. However, the dispersion of these models, especially to the United States, has been slow. Nearly 20 years ago, ABET published the a-k student outcomes, requiring engineering programs to graduate new engineers with many of the attributes listed above. Despite this, the pedagogies didn’t change and the attributes are not developed in the majority of engineering graduates. This chasm resulted in the initiation of an idea that turned into the development of a PBL model in the rural iron range region of Minnesota. Using the Aalborg model of PBL as a starting point, the Iron Range Engineering model of engineering education began in 2010. Through continuous improvement it has constantly evolved through the present day. This model of PBL is the backdrop for this study. Volume 1 takes a deep look at the theoretical underpinnings of the

model and provides a detailed description of both the model and the change processes involved in the model's development.

The skills associated with being a self-directed learner (SDL) and the relationships between PBL and the acquisition of SDL skills are the focus of the research study in Volume 2. The theoretical perspective aims to explore how metacognition, self-regulated learning, lifelong learning, and motivation impact self-directed learning development. The literature review identifies a strong positive correlation between self-directed learning development and PBL learning environments. Quantitative research was designed to study the graduates of the Iron Range Engineering program to identify if the correlation exists in that PBL environment and how it compares to graduates of traditional engineering programs. The correlation from the literature was confirmed. The PBL graduates achieved significant SDL development whereas the traditional graduates did not. This result prompted the development of a qualitative study to explore the ways in which the PBL graduates experienced self-directed learning. Two models of understanding are presented. The first is a phenomenographic outcome space that identifies the various ways students encounter self-directed learning. The second is a detailed composite model describing all of the elements of self-directed learning that the PBL graduates employ and the processes through which they do so. The results of this research provide opportunities for curriculum developers and engineering instructors to contemplate how PBL curricula can be used in the development of the engineering graduates of the future.

DANSK RESUME

Ingeniøruddannelse er ved en korsvej. Fremtidens ingeniørkompetencer rækker langt udover analytisk viden som var i fokus for fortidens ingeniører. Fremtidige ingeniører skal være kreative, opfindsomme og fleksible . De skal have stor dygtighed som kommunikatorer og professionelle. Frem for alt skal de være talentfulde selvstyrede lærende. Fortidens ingeniøruddannelse gav eksplicitte muligheder for studerende til at udvikle stærke analytiske evner, men kun implicit læring af disse andre vigtige egenskaber. For at fremtidige ingeniører skal udvikle et højt niveau af dygtighed, skal størstedelen af deres tid i auditorier og arbejde med hjemmeopgaver forblive en del af ingeniøruddannelsernes fortid. Hvis vi ønsker at de studerende skal tilegne sig komplekse færdigheder, har de brug for tid til at øve disse færdigheder og modtage rigelig formativ feedback på udvikling af disse.

Projekt - baseret læring (PBL) er en pædagogik der understøtter udvikling af ingeniørstuderendes kompetencer. I PBL, arbejder de studerende i grupper og anvender ingeniør designprocesser til komplekse, åbne problemer. De udvikler sociale kompetencer, konflikthåndteringsstrategier og professionelt ansvar. De skriver tekniske ingeniørmæssige rapporter og giver professionelle ingeniørpræsentationer. Deres motivation for at lære bliver aktiveret, fordi de har indflydelse, får realistiske udfordringer, og muligheder for at samarbejde med hinanden og blive relateret til deres fremtidig erhverv.

De udvikler identitet som spirende ingeniører og de påtager sig ansvaret for at styre deres egen læring af teknisk-faglig viden. De lærer, hvordan man lærer. De bliver selvregulerende , metakognitive, selvstyrede studerende. Ingeniører der er uddannet fra PBL universiteter er mere klar til professionel praksis og ligner mere den fremtidige ingeniør.

De færdigheder der er forbundet med at være selvstyrede lærende, og forholdet mellem PBL og erhvervelse af selvstyrende færdigheder er fokus for forskningen i anden del. Det teoretiske perspektiv har til formål at forklare, hvordan metakognition, selvregulerende læring, livslang læring og motivation indvirker på udviklingen af selvstyret læring. Litteraturstudiet identificerer en stærk positiv korrelation mellem udvikling af selvstyret læring og PBL læringsmiljøer. Den kvantitative forskning er designet til at studere kandidater af Iron Range Engineerings program for at identificere, om sammenhængen eksisterer i dette PBL miljø. Endvidere foretages komparativ analyse mellem med kandidater fra PBL miljøet og de traditionelle ingeniøruddannelser. Relationen fra litteraturen blev bekræftet. PBL kandidater opnåede betydelig udvikling af selvstyret læring, mens de traditionelle kandidater ikke gjorde. Dette resultat tilskyndede udviklingen af en

kvalitativ undersøgelse for at udforske de måder, hvorpå PBL kandidater oplever selvstyret læring. Metodisk anvendes phenomenographic tilgang, der identificerer de forskellige måder, de studerende møder selvstyret læring. Teoretisk sammenstilles en detaljeret model, der beskriver alle de elementer af selvstyret læring, som PBL kandidater arbejder med og de processer, hvorigennem de gøre det. Resultaterne af denne forskning giver studieordningsudviklere og tekniske instruktører input til at overveje, hvordan PBL studieordninger kan bruges i udviklingen af ingeniører i fremtiden.

ACKNOWLEDGEMENTS

This work is dedicated to every student who has ever shared his or her education with me. Without them, none of this matters. In particular, the following students, unbeknownst to them, inspired me to deeply reflect on learning:

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Throughout my teaching career several colleagues, have had a profound impact on my teaching. In particular, the following: *Marguerite Roza, Aaron Wenger, Carol Wenger, Ivy Hanson, Bart Johnson, Glen Hodgson, Gordy Savela, Crystal Smith, Jamie Kleinendorst, Derek Fox, Eric Ahlstrom, Dan Ewert, Andy Lillesve, Elizabeth Pluskwik, Jim Boyd, Christine Kennedy, Becky Bates, Mike Alpaugh, Mike Johnson, Joe Sertich, Barbara McDonald, Bill Maki, Bill Sackett, Bill McBride, and Nick Lefebvre*. I greatly thank them for shaping my teaching and learning.

The love and support from my family has served to emotionally empower me throughout a teaching career and through this PhD experience. I thank my parents, *Ron & Wanda* and *Molly & Glenn*, my children, *Katie & Colin, Liz, Ron & Katy*, my grandchildren *Ethan, Elise, Liam, and Molly Rose*, and the many members of this extended family of educators.

I wish to give a special thank you to those who helped by giving me their time to read this paper and suggest edits: *Angie, Glen, Jessica, Pia, and Wanda*.

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In the early 2000's, *Brian Winkel, Jim Richardson, Dan Ewert, Jeff Froyd* and I dared to dream about the realization of a new model of engineering education in the United States. This dream inspired Iron Range Engineering. Iron Range Engineering serves as my daily motivation as a professional and is the central topic in this thesis. Thank you Brian, Jim, Dan, and Jeff.

The entire staff of the UNESCO PBL Center who welcomed us as colleagues and who guided us on this journey.

My deepest gratitude is owed to those without whom this work would have never been started, nor completed: our exceptionally kind and gracious advisors who guided us so adeptly, *Anette Kolmos & Erik de Graaff*, my close colleague, *Becky Bates*, the incredible *Claus Spliid* whose insight has inspired us from the beginning and whose bread nourished us, my co-innovator at Iron Range Engineering, *Tom Rukavina*, and my co-author and close friend *Bart Johnson*, without whom most days of this work would not have started. A special thanks also goes out to *Jessica & the Johnson family* for supporting Bart through this work.

Finally, I dedicate this work to the love of my life, *Angie*, who sacrificed years of family time, supported me through the work, used her vast knowledge of education to provide insight, and who inspires me every day to be a better person.

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FOREWORD

The perspective of experience brings with it a much different lens than when I made a first attempt at PhD studies, 20 years ago. I have a broader sense of purpose as a learner and a guide for others' learning. I have a greater appreciation for how each individual's experiences establish his or her reality, meaning there is not just one reality, rather one for each person.

The first undergraduate course I taught was thermodynamics, in the spring of 1989. At the time of this PhD defense, I will have completed 27 years of teaching 8-10 undergraduate engineering courses per year, meaning I have taught over 200 semester-length courses. There are four distinct phases that I went through in this time.

In phase 1, I mimicked my undergraduate professors. I lectured, assigned large homework sets, gave three exams per course, and had rigorous grading standards. I tried to be engaging in the classroom and found that students seemed to enjoy taking my courses.

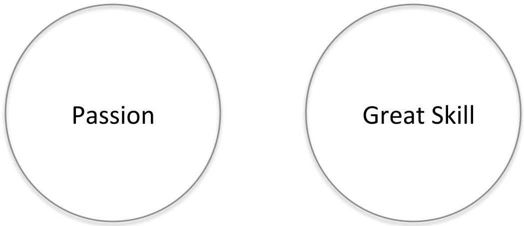
As time went by, I discovered the power of learning communities. Students, when given the time and space to be in contact with one another and me outside the scheduled class hours, began to thrive. The groups quickly gathered the identity of emerging engineers, and the individuals followed suit. In this second phase, I began to focus more on the individual, taking on an empathetic role as a personal coach, inside and outside the classroom. The feedback I received was quite positive. Students outwardly acknowledged enjoying my courses. Graduates who entered the workforce often commented that I was a critical person who empowered their successful journey into the profession. Near the end of this phase, approximately 15 years into my career, I made the following statement in a formal evaluation with my Dean: "I am a master teacher. I have arrived." In my perception at the time, there was excellent evidence in support of the statement. Our engineering program had grown from 10 students to over 100. We had secured millions of dollars in funding based on our successes and had even acquired funding for a new facility that was designed specifically for our learning communities.

Still, in the back of my mind, something seemed off. It would come to the forefront each time I would teach a course, such as mechanics of materials. There was a pre-requisite course (statics) from which the students should have brought essential knowledge. Most students did not bring the knowledge forward. Usually, when this happens, it is easy for the instructor to blame the previous instructor. This is much harder when the previous instructor is oneself. It was quite confusing for me. These students seemed to love statics. They worked hard. They did very well in the course. Yet, they didn't learn the material well enough to access and use it in the next term. At this time, the How People Learn (Bransford, Brown, and Cocking, 2000) movement began to emerge. The ideas and power of active learning were reaching us through publications that made their way to campus. I entered phase 3 of my teaching, in which, for several years I redesigned the classroom experience, changing it from a one-way delivery of information into an interactive, collaborative, building of knowledge. I began attending national and international engineering education conferences, almost always bringing home a new idea to implement in my courses. I began to see what worked for student learning and to continuously refine the methods.

There was still, however, a growing desire in me wanting more. I began to be no longer satisfied with "what" worked. I wanted to know "why and how" it worked. My colleague, Bart Johnson, had shared the third phase of my teaching development with me. He shared my passions for wanting to improve the student learning experience. Through a set of fortunate circumstances, we were presented the opportunity to undertake this PhD study under Erik de Graaff and Anette Kolmos at Aalborg University.

A whole new world of understanding has emerged. I now have theoretical frameworks for making sense of the learning of students. I now see that the successes in my mid-career can be seen through the perspectives of motivation, as presented by Deci and Ryan's self-determination theory (see Chapter 5). I now look through the lens of Illeris' triangle to develop learning experiences, as well as through the lens of the American Psychological Association's (APA) learner-centered principles (see Chapter 2). These three theoretical perspectives form the spine of the work done in this thesis. Many others are presented and have added to my knowledge base. However, the value of this PhD study goes much deeper than the understanding of new knowledge. This experience has brought new ways of thinking and acting. Our supervisors have, through kind-hearted feedback, helped shape us into emerging researchers. There now exists a personal passion for the discovery of new knowledge that was not evident before.

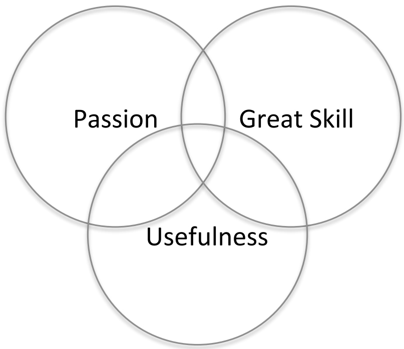
One further motivation that has emerged is a sense of purpose and value. The author of the popular book, Good to Great, Jim Collins (2001) discusses something he calls the hedgehog concept. It is a Venn diagram in which three circles intersect. The three circles regard a person's life work. Circle one is finding work that you are very passionate about. Circle two is about finding work in which you have great skill.



Foreword Figure 1. Partial hedgehog concept

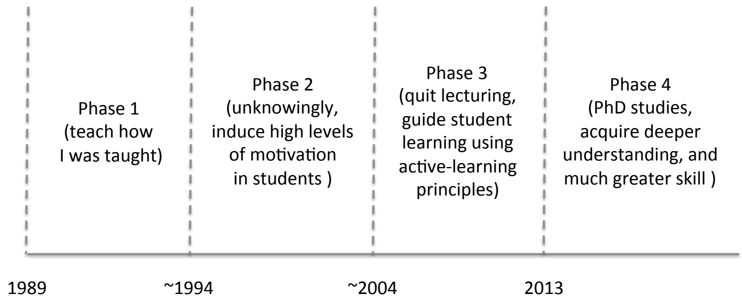
It is easy for me to say I have a great passion for assuming the role of empowering the learning of others. Judging one's own greatness in skill is a very different thing. I can provide much internal evidence to the contrary. However, there is much external evidence that would say I am at least one standard deviation above the average. I will settle with this, and find comfort that I can, at least continue forward to look at the third circle.

The third circle is about doing work that is useful. Without controversy, we can easily call the work of this profession useful. Collins claims that few people can find life's work at the intersection of passion, skill, and usefulness. My perception at the time of this writing is that I am there. (However, I am cautious due to my statement many years ago about being a master teacher.) The work of this PhD has increased my passion and increased by abilities at the student-teacher interface.



Foreword Figure 2. Hedgehog concept

The experience of earning this PhD has motivated me to be more useful. The challenge and success of being a critical guide in the future career of a young person are usefulness, at its core. This PhD has empowered me to be more useful. I highly value this impact of the experience.



Foreword Figure 3. Four phases of teaching career

In summary, my life as an engineering educator can be looked upon in the four phases described above. The experiences of phases one through three motivated me to start a PhD experience. The start of phase four coincides with the start of PhD. Phase four has been my continued career as an engineering educator, and now researcher. In phase four, I have nearly quit using the words student and teacher. This PhD experience has me believing that I really can't teach anybody anything of value (See Carl Rogers quote in chapter 5). The act is much more about empowering people to learn on their own. The PhD experience has brought a new set of motivations: deeper motivations to learn, stronger motivations to help individuals learn, and motivations to contemplate my usefulness to society from the greater perspective of one's own life work. I look forward to some day writing about phases 5, 6, 7…

From the completion of this PhD study, looking back to the beginning, I perceive a value of the experience at a level I would not have expected. That value is the impact of the PhD study on the development of the student learning experience in the IRE program. A great deal of that value comes from the literature that was accumulated while creating the theoretical perspectives in chapter two (volume one) and chapter five (volume two).

This literature provided a rich set of ideas to contemplate implementing, both in the daily classroom interactions and as curricular changes at the program level. Further, the knowledge I gained presented new perspectives that changed my behaviors and altered my beliefs, both of which impacted the program's implementation.

An example would be that Deci and Ryan's self-determination theory (SDT) on motivation has greatly influenced how I interact with students, and through its explicit exposure to students framed the ways they look at their own learning. It is common to hear students reflect on the role of autonomy in their PBL experiences. This is directly from their learning of SDT, which came from my learning it during this PhD study. Examples like this are numerous and, from my perspective, have substantially altered the development trajectory of the entire program.

CHAPTER 1. INTRODUCTION

(RON ULSETH AND BART JOHNSON)

Currently in engineering education, there is a movement of change. It comes at a time when societies around the world are facing the challenges of the 21st century and beyond (www.engineeringchallenges.org). As with past challenges successfully met by societies, engineers need to be a crucial part of meeting these future challenges.

However, the nature of these 21st-century challenges is different than those of the past. "Engineering has to be seen in a very much broader context in terms of its role and impact on the society, and engineers need to have a very broad set of skills in addition to their engineering expertise" (National Academy of Engineering, 2005). Desha, Hargroves, and Smith (2009) identify that society also has a different expectation for engineers addressing these challenges that will require them to provide solutions that go well beyond just a technology focus and also involve "human values, attitudes, and behavior, as well as the interrelationships and dynamics of social, political, environmental, and economic systems on a global basis" (Splitt, 2003). This means that engineering education needs to adapt its model to graduate engineers ready for this new role.

This thesis is the result of the collaboration between two PhD candidates, Ron Ulseth, and Bart Johnson. Since 2010, we have been involved in the development and implementation of the new Iron Range Engineering (IRE) program, a program that emerged as a result of the calls for change. The IRE program started as an adaptation of the Aalborg model of engineering education and consists of the third and fourth upper-division years of an engineering bachelor's degree. The IRE model is based on student attainment of technical and professional competencies while working on industry projects. IRE started accepting students in January 2010. At the time of this PhD defense, 95 students had successfully completed the degree and 60 additional students were currently making satisfactory progress towards degree completion. The IRE model is ever evolving. It is the product of an engineering educator practitioner's approach to curriculum development. It has been successful in the sense that students are readily received by industry as valuable members of the profession. The program received initial accreditation by ABET. However, for the IRE program to continue to improve and viably develop its ability to impact engineering education, its development process and the current educational model need to be evaluated and improved from an engineering education researcher's approach. Our goal in the PhD experience was to gain the research perspective to bring to bear on the IRE program.

Within this context, each candidate developed an individual research program. Of particular interest to Johnson was the development of professional competencies by students. Ulseth chose to investigate the impact on students' attainment of self-directed learning (SDL) abilities. Thus, the two research studies to be undertaken were:

1. Mixed-methods explanatory study of the professional competency development by PBL students. (Johnson)
2. Mixed-methods study of the self-directed learning experience of PBL students. (Ulseth)

One of our motivations was to apply change, curricular, and learning theories to analyze the development and implementation of the IRE model. We desired to understand our experiences of success and failure as viewed from the perspectives of theory, something that was not done during the development and initial implementation. We worked closely together to write the first volume. This collaborative work analyzes the Iron Range Engineering model. The analysis starts with a theoretical perspective on the aspects of change, curriculum, learning and PBL (Chapter 2). The perspectives are then used to detail how the Iron Range Engineering program came about (Chapter 3 – History) and to describe the details of the model (Chapter 4 – Iron Range Engineering).

Johnson's thesis includes the shared volume one and his own volume two covering the professional competency development study. Ulseth's thesis includes the shared volume and his own volume two on self-directed learning.

1.1. CALLS FOR CHANGE

In this volume, we analyze the theories used in the development of the Iron Range Engineering program. Presented first is the context in which the Iron Range Engineering program was developed with a focus on why the need for change, what is required from a new model of engineering, and how it can be achieved.

The need for change resulted from the recognition of engineering education being at a crossroads. Does it continue down the current path or change course to respond to the calls for changes (Graham, 2012b)? Making this decision requires knowing what are the calls for change and what can be achieved by heading down the new path.

On a global level, UNESCO commissioned and released two important reports: *ENGINEERING: Issues, Challenges, and Opportunities for Development* in 2010 and *Engineering Education: Transformation and Innovation* in 2013, to focus attention on making engineering education "more interesting and relevant at a time of changing global need, issues, and contexts" (Beanland & Hadgraft, 2013). The reports emphasize the importance of engineering and engineers for providing the technological developments needed by society. At the same time, they identify the undersupply of engineering graduates in countries around the world and the very low percentage of formal graduates, which is creating substantial gaps, in most countries, between the number of graduating engineers and the number of engineers required to meet their nation's needs. The need for promoting engineering and engineering careers to the public to create greater awareness of the importance of and career opportunities provided in the engineering field is clearly evident.

Nationally, research and study findings in Australia, the U.K., and the U.S. are also expressing concerns over an insufficient supply of engineering graduates who are equipped to meet the current and anticipated needs (Institution of Engineers, Australia 1996, Royal Academy of Engineering 2007, Engineering, 2005). One identified step to overcoming this shortage is shifting student perceptions of engineering towards finding it as an exciting and rewarding profession that is worth pursuing. Additionally, they also identified the need for universities, and industry, to make engineering education content align more closely with the actual professional practice of engineers to equip graduates with the competencies and attributes necessary for practice.

There is an evident concern for the widely held view that "many contemporary engineering graduates are deficient in the capabilities that are required of engineers" (Kolmos, 2013). A gap exists between engineering education and the current and future needs of the engineering profession. This global situation has led to international calls for transformative change in engineering education. The 2010 UNESCO Report on Engineering: Issues, Challenges, and Opportunities notes that:

> "One of the greatest challenges for engineering is the need to make engineering education more interesting and relevant at a time of change in global needs, issues and contexts, such as the rising concern regarding climate change, and the opportunities provided by information and communication technologies in engineering and engineering education. There is a particular need for the university and other courses to be reviewed in terms of the appropriateness of the desired outcomes, the effectiveness of the learning and teaching approaches, and the appropriateness of the curricula. It will be suggested that it is possible to emphasize the development of engineering skills and expertise through a problem-solving approach with application to address both local and global issues such as poverty reduction, sustainable development, and climate change mitigation and adaptation."

The follow-up 2013 UNESCO Report, Engineering Education: Transformation and Innovation, identifies that educational institutions will not accomplish this by themselves. The elements necessary for this change will need to come from external stakeholders (Beanland & Hadgraft, 2013), including:

- Major Engineering Employers
- Professional Organizations
- Governments

In the United States engineering education system, these three stakeholders have joined to make several extensive calls for engineering education to create a new model of engineering education, including:

- National Academy of Engineering's "The Engineer of 2020" (2004)
- National Academy of Engineering's "Educating the Engineer of 2020" (2005)
- National Science Board's (2007) "Moving Forward to Improve Engineering Education

These calls focus on the societal needs for a "new look" engineer and they address that the engineering education model needs to transform the engineering curricula from engineering content knowledge transmission to the "development of skills that support engineering thinking and professional judgment" (Adams & Felder, 2008). Such a redesign of engineering curriculum requires a focus on the product that it produces and a significant shift away from the current status of the inward focus on the organization of the engineering education curriculum itself, as so many engineering education improvements have been focused on, to date, in the U.S., and around the world.

In Europe, the Bologna Process emphasizes the importance of improving engineering graduates' competencies in innovation and entrepreneurship (Communiqué, 2009). The Royal Academy of Engineering (Spinks, Silburn, & Birchall, 2006) study of "Educating Engineers for the 21st Century" also makes several findings regarding the need for transformation of engineering education including:

- Universities and industry need to find more effective ways of ensuring that course content reflects the real requirements of industry and enables students to gain practical experience in industry as part of their education.
- Much more needs to be done to ensure that school students perceive engineering as an exciting and rewarding profession that is worth pursuing.
- Unless action is taken, a shortage of high caliber engineers entering industry will become increasingly apparent over the next ten years with serious repercussions for the productivity and creativity of industry.

A significant step identified by the international community to eliminate the gap between educational and industry expectations for engineering students commenced in 1989 with the professional organizations and institutions from Australia, Canada, Ireland, New Zealand, United Kingdom, and the U.S. forming what would become the Washington Accord. Several countries from around the world have since joined it (Beanland & Hadgraft, 2013).

The Washington Accord sought to establish standards for professional competencies and develop attributes of engineering students graduating from an accredited institution. Specifically, it creates a competency focus for engineering education and broadening the focus of engineering education to include preparation for professional practice. Lemaitre, Prat, Graaff, and Bot (2006) confirm that the preparation "of students for professional competence has always been the ultimate goal of engineering curricula".

In the U.S., the Washington Accord led to ABET, the non-governmental accrediting body for the U.S. engineering education system, introducing a new set of engineering accreditation criteria, ABET Engineering Criteria 2000 (Abet.org, 2015). Of greatest significance to changing engineering education was the General Criterion 3 student outcomes, also known as the ABET Criteria. This set of outcomes reflected a movement in the U.S. towards a focus on the student development of their professional competencies and attributes. Similar movements were taking place in other countries around the world. In the United Kingdom, the application of the Washington Accord was through the Engineering Council UK. In Australia, Engineers Australia established the competency standards.

It is evident that the time has arrived for engineering education to go beyond the current state of focus on cutting-edge technology and increasing knowledge acquisition, and move toward an equal focus on all aspects of engineering practice and scholarship (Denning, 1992; Goldberg & Somerville, 2014; Pister, 1993; Prados, 1998; Splitt, 2003). Satisfying the demand for change within the current traditional curriculum will be very difficult, if even possible (Fromm, 2003). A new paradigm, a new model, in engineering education is needed.

1.2. REQUIREMENTS OF NEW MODEL OF ENGINEERING

This need for a new paradigm is generating much discussion about what should be the "nature, context and curricula of undergraduate education" (UNESCO, 2010). This dialogue is influenced by the rapid expansion of knowledge, changes in engineering practice, concerns for attracting adequate numbers of students into the engineering profession, and change requirements of employers. While the need is evident for transformation of engineering education to match the changes in the engineering profession, very few have actually changed to a new instructional model. In the U.S., Walther and Radcliffe (2007) identified that despite the interest by universities and engineering faculty throughout the U.S. in changing to meet the needs of the profession, the engineering education system is still not providing graduates with the competencies identified as needed by industry.

In *Educating Engineers: Designing for the Future of the Field*, a study of engineering programs at several U.S. institutions also identified that not much has changed in the engineering education system regarding the design of the curriculum to meet the professional competency needs of the engineering profession (Sheppard, Macatangay, Colby, & Sullivan, 2009). Study results indicate, "undergraduate engineering education in the USA," and in most other parts of the world, "is holding on to an approach to problem solving and knowledge acquisition that is consistent with practice that the profession has left behind." It found that the engineering curricula were still heavily biased towards analysis to the detriment of professional skills development as well as other areas of engineering.

Of further concern is noted by van der Vleuten (1997) that often as change is attempted, faculty appear to use intuition as the approach to improving teaching and student learning instead of using a scientific approach. Most educational experiences are still based on an assumption that the development of professional competencies can occur in a set of discrete finite episodes with a beginning and end (Wenger, 1998). This is despite the fact that students and employers, alike, expect a higher degree of synergy between what is learned in the classroom and what is needed in the field (Passow, 2012).

Goldberg and Somerville (2014) provide three lessons from the history for engineering education as transformation is sought. First, the change that is needed cannot be accomplished with small changes to existing curriculum. Second, students are "sensitive to the world of work and to the culture of the education system". In agreement with Passow, a high degree of synergy is needed between the engineering education experience and the profession. Third, change management attempts to date have not been successful. New bold approaches are needed to accomplish the change.

There is growing concern that the continuation of the old paradigm of engineering education will not only not prepare graduates to meet these challenges, but will also lead to engineers being relinquished to minor roles in meeting the 21st-century challenges facing society (Splitt, 2003). The 2013 UNESCO Report on "Engineering Education: Transformation and Innovation" (Beanland & Hadgraft, 2013), states that

> "It is widely acknowledged that engineering education requires a transformation to produce graduates, in sufficient numbers and with appropriate knowledge and skills, to proved the capabilities to address the

> many technological issues and projects at are required for the development of our communities."

The report outlines a vision for the key steps or principles for transforming the "design and implementation of an effective engineering curriculum":

- The first step towards Transformation is the adoption of the Washington Accord Graduate Attributes as the goals of each engineering education program to be realized by every graduate.
- The second step towards Transformation is to design the curriculum to maximize the development of the capabilities that are essential to operating as a professional engineer.
- The third step towards Transformation is the design and implementation of the first year of the engineering education program to maximize student motivation.
- The fourth step towards Transformation is the utilization of Project-based Learning in each year of engineering education programs.
- The fifth step towards Transformation is the replacement of the information-transmitting lecture in engineering education programs with activities that generate student-centered learning through the active involvement of students which creates thinking aimed at developing understanding.
- The sixth step towards Transformation is the utilization of the wide range of information technology and communication systems and resources to facilitate student-centered learning.

A similar guiding strategy for curriculum improvement is provided in *Educating the Engineer of 2020* (National Academy of Engineering, 2005). It proposes that effective improvements for engineering education in the U.S. must focus on the whole educational system and move beyond the current ineffective approach of incremental improvements to single aspects of complex curriculums. The publication promotes a systems level educational approach that, at a minimum, incorporates the following elements:

- Application of engineering processes to define and solve problems using scientific, technical, and professional knowledge bases
- Engagement of the engineer and professionals from different disciplines in team-based problem-solving processes
- Tools used by the engineer and other technical professionals
- Interaction of the engineer with the customer and engineering managers to set agreed-upon goals;
- Economic, political, ethical, and social constraints as boundary conditions that define the possible range of solutions for engineering problems and

> demand the interaction of engineers with public" (National Academy of Engineering, 2005).

Rompelman and De Graaff (2006) also proposed that engineering education curriculum should be developed from a systems approach. In the systems approach, they propose that an educational process is one that transforms students from their the state of their initial attributes as they enter an engineering program to a state of graduate attributes as they complete the education process. The proposed premise is that the learning process is one where the learner "constructs knowledge on the basis of prior knowledge and additionally acquired information." This process is based on a constructivism perspective (Jonassen, Pfeiffer, & Wilson, 1999).

1.3. ACCOMPLISHING CHANGE

Achieving a system level educational change is difficult to accomplish (Kotter, 1995) and represents a significant departure from the current model of engineering education around the world and especially in the U.S. It is a difficult process to transform the complex and diverse system that engineering education is with its large number of variables (Beanland & Hadgraft, 2013). Even more difficult is maintaining the change once it is accomplished (Graham, 2012b).

In the Royal Academy of Engineering and MIT commissioned report, Achieving Excellence in Engineering Education: The Ingredients of Successful Change (Graham, 2012a), identifies the pressing issue for engineering education, is not whether to change, but how to change. In its two-stage study of successful change, three common features were identified for the designing of successful programs of change.

First, successful change requires it to be about the entire curriculum structure. The new structure must be interconnected and coherently support the change being attempted. Second, successful change requires the curriculum structure be developed with curriculum goals in mind by the entire cross section of faculty. Graham notes that this part of the curriculum design is necessary regardless of the scale involved with the change. The Third, successful program changes are ambitious and aspire to develop a new "brand for the education approach". The aspect of creating a national or international education model is a motivating factor in engaging the faculty to create and sustain the change.

Committing to such a significant level of change in the development of the new curriculum for this research work requires a curriculum development process that is framed within the context of both the state of the art for curriculum theories and the state of the art of learning theories. The magnitude of the change in developing a new engineering curricular approach requires the curriculum development to be framed within change theory. These will be developed in chapter 2.

1.4. PBL IN CALLS FOR CHANGE

The report by 2013 Graham and the UNESCO reports identify PBL as an integral part of successful curricular changes and as one of the key steps in the "design and implementation of an effective engineering curriculum," respectfully. Graham's study revealed that a majority of the highly regarded examples of change involved the use of PBL within an "authentic, professional engineering context." Project-based learning is a core theme throughout the 2013 UNESCO report to achieve the Washington Accord graduate attributes and to provide the "personal learning experiences" needed for the transformation of engineering education. It identifies that,

> "Project-based Learning (PBL) is a widely reported approach to address the need to change engineering education, from the formal presentation of technical material to a student experience model. It provides activities, which simulate the role and responsibilities of practicing engineers, and develops the general graduate attributes that have been identified as essential. It was first used in medical education and is now extensively used as it promotes the development of the skills and knowledge required by medical practitioners… Project-based Learning can be organised for individual work, but there is greater benefit from having the project under- taken by a team of students. This relates more closely to a realistic engineering environment, provides an opportunity for students to learn from each other, and assists the development of the essential graduate attributes of team- work and leadership."

The Cambridge Handbook of Engineering Education Research is a new reference source for the "growing field of engineering education research" (Johri & Olds, 2014). The book focuses on five key themes identified by the U.S. National Science Foundation and published in October 2006 in the *Journal of Engineering Education.* The second section of the handbook, "Engineering Learning Mechanisms and Approaches," focuses on approaches for transitioning from traditional to a variety of active student learning approaches in engineering education. This section begins with an explanation of problem-based and project-based learning models by Kolmos and de Graaff, as an example of the curricular approaches engineering education should be considering.

Throughout the engineering education literature, it is evident that PBL should be strongly considered in the development of a new or the change of an existing engineering program. In the development of this new program, PBL and PBL theory are an integrated core component of the curricular model.

1.5. DESCRIPTION OF IRON RANGE ENGINEERING

Using the perspectives of change theory, curricular theory, learning theory, and PBL theory, which are presented in Chapter 2, the program is first presented in its historical context (Chapter 3). Then the current model of the program is thoroughly detailed through the inclusion of its curricular makeup, pedagogical approaches, space considerations, and its people (Chapter 4).

1.5.1. OBJECTIVES

1. Describe the motivations behind the start of the Iron Range Engineering program.
2. Describe the Iron Range Engineering program through theory.
3. Explain the evolution of the Iron Range Engineering.
4. Show how the curricular elements of the Iron Range Engineering model are implemented.
5. Detail how the Iron Range Engineering program implements the principles of PBL.

1.5.2. BACKGROUND

In 2010, the new model of project-based learning began in the iron-mining region of Minnesota in the United States. This program was adapted from the Aalborg University model of PBL in Denmark. At the time, curricular level PBL in engineering education in the U. S. was rare. The program developers were motivated by the calls for reform in engineering education to better align educational experiences and outcomes with expected competences needed in engineering practice.

Embracing core values of continuous improvement, professional responsibility, the power of reflection during learning, industry-sponsored projects, and self-directed learning, the implementation team began the new model of PBL. This model became a social construct of the students, professors, industry clients, and communities.

The development and implementation teams faced adversity on many fronts as the new model strove for acceptance in the engineering and academic communities. That acceptance slowly arrived as graduates found success in their positions and the program attained ABET accreditation.

1.5.3. ANALYSIS FRAMEWORK

Volume 1 is an analysis of the Iron Range Engineering program bounded on one end by the inception of its existence and the other by the completion of the PhD studies. The Iron Range Engineering PBL program is analyzed from three distinct perspectives: theoretical, historical, and descriptive. Chapter 2 develops the theoretical perspective for the aspects of change, curriculum, learning and project-based learning that were applied in the development of the program. These theoretical aspects are used in Chapters 3 and 4 to analyze the program. Chapter 3 develops a historical description of development and analyzes this process in relation to the change theory. Chapter 4 describes the current program and provides a descriptive analysis within the theoretical framework of curriculum, learning, and PBL.

At the conclusion of Volume 1, the results of this analysis will be presented. The results will include a set of key findings for consideration by engineering education and those individuals involved with curricular change decisions. Throughout Chapters 3 and 4, these key findings will be highlighted as they are first identified.

In addition to literature review resources used in Chapter 2, a variety of data was available for developing the analysis for Chapters 3 and 4. First, was the abundance of printed documents in the forms of syllabi, student handbooks, and faculty handbooks from each of the years of the program's existence. The documentation for the current program description was collected from the program directors in the forms of syllabi, faculty and student handbooks, the program website and wiki, through access to a wide set of documents on their shared document collection.

Second, there was a large set of published materials available: materials from members of the development team longitudinally while the program was being created, initially implemented, and achieving a steady operating state; materials published by the current program personnel, and media publications written about the program. These artifacts are available from the beginning of the idea to the present time.

Third, the personal accounts of the researchers' direct observation were also employed. The researchers lived through the entire evolution of the program as members of the initial development and implementation teams. Ulseth has observed the daily implementation of the program throughout its entirety.

Attempts have been made to mitigate any bias through the use of artifacts to substantiate all descriptions. Member checking by having other members of the development and implementation teams was employed to reduce this bias by having them read the descriptions checking for accuracy and varied perspectives. The situation of having two researchers in this study also provided the opportunity for frequent peer checking of facts and processes. These iterative discussions added substantially to the depth of the analysis as well as in the elimination of errors. The data is presented in deep detail in an attempt to achieve a rich description.

1.6. CONCLUSION

It is at the intersection of our personal motivations, the widespread calls for change in engineering education, and the implementation of the Iron Range Engineering program that this PhD work begins and ends. This intersection represents the themes present in this undertaking: 1) the development of us as individuals from being reflective practitioners to being both practitioner and emerging researcher, 2) the opportunity and obligation to contribute new knowledge to engineering education, and 3) a desire to use new found knowledge to continuously improve the Iron Range Engineering model of learning.

This section is written after all other chapters are in draft form. The PhD process has been successful in transforming us as individuals. For our combined 35 years in academia, we have been active, innovative, and reflective practitioners with the perspective for the opportunity and passion to improve engineering education. The PhD process has significantly broadened this perspective and allowed us to be able to reflect and analyze in an academic way, to include theory and research, our work.

This process of growth comes with struggles to begin to think like researchers and to write like academics. The patience and guidance of Anette Kolmos and Erik de Graaff allowed the transformation to begin and to progress. We are thankful for this opportunity to continue our work with engineering education now empowered more as academics.

As alluded to in Section 1.3, the calls for change in engineering education have existed for decades and have gone largely unheeded. The motivations for starting Iron Range Engineering were rooted in the desires to design and implement a curriculum that better aligned with the needs of the profession and contributed to the development of engineering education.

The first six years of the curriculum's implementation yielded experiences and results that, when properly disseminated, provide knowledge for others to consider. The knowledge themes of potential value include the change process experienced during startup, the unique approaches taken to align with the professional competence needs of the profession, the model of continuous improvement embraced by the program, the developmental trajectory taken by the program, and the metacognitive and reflective development of the self-directed learners.

At question is whether this research should be conducted externally by those who had no part in the program's operation, or internally by those who lived the experience. We believe the answer is both, that each perspective has potential value. As people who lived the experience, we did do the research in our PhDs. At the time of the PhD defenses, two additional, external research projects on these topics are in progress. Thus, substantial steps are being made, in attempts to meet the obligation of contributing new knowledge to academia.

CHAPTER 2. THEORETICAL PERSPECTIVE

(RON ULSETH AND BART JOHNSON)

The description of the IRE program, it development, and analysis starts with a theoretical perspective on the aspects of change, curriculum, learning and project-based learning. Each of the aspects will be developed in its own section. Each section will conclude with the applications from the theoretical perspective to be used in the description, development, and analysis of the IRE PBL program.

2.1. CHANGE THEORY

"Good ideas with no ideas on how to implement them are wasted ideas."
(Fullan, 1982)

With such widespread agreement on the need to transform engineering education, why is there, then, an apparent lack of response from engineering universities to transform to meet this need? (Beanland & Hadgraft, 2013; Graham, 2012a, 2012b; Singer, Nielsen, & Schweingruber, 2012). One key part of this question is how to develop a successful process of change to respond.

In developing the Royal Academy of Engineering and MIT commissioned report, Achieving Excellence in Engineering Education: The Ingredients of Successful Change, a two-stage study of successful changes in engineering education was conducted (Graham, 2012b). In the first stage, interviews of 70 international experts from 15 countries were conducted to provide insight into curriculum change. The second stage was focused on 6 case examples, with an additional 117 individuals interviewed to further understand the curricular change. This study, led by Ruth Graham, identified common strategies for successful change that can be summarized in three phases:

> <u>Phase 1: Preparatory Work</u> – This consists of first gathering local evidence for the need for change, and then benchmarking other educational approaches. This is followed by generating an early broad vision for change, first to senior management and then to faculty. This is a critical step in the process of gaining the support of leadership and faculty and requires an emphasis on the change and the drivers for change. It is important not to look at a solution first. Otherwise the focus shifts to the personal impact on each of these individuals and thus diverts away from the solution.

> Phase 2: Planning for the Change – once the decision has been made for changing, the "underpinning educational approach" that is unique to the institution should be determined. Then faculty involvement in a blank slate approach to a new curriculum design is critical for optimizing support for the change.
>
> Phase 3: Implementing the New Approach – an implementation team of respected individuals should be released from other duties to focus solely on the implementation of the new approach. Key aspects identified in the study for implementation success included frequent demonstration of benefits to students and faculty involvement with the new approach. The implementation speed and phases varied in the study, but all changes were implemented in a "single, concentrated effort over a 2-4 year period and called for considerable faculty-wide attention during that period." Reform changes all took at least five years to implement.

It is apparent that the transformation of engineering education must be viewed as a process and not as an event (Fullan, 2001). Given the complexity and the difficulty of successful change processes (Blackmore & Kandiko, 2012) and that less than 35% of change efforts produce enduring, significant change in the operation of an organization (Kotter, 1996), a change model is necessary to view the development of this program. In this section, a framework for the change, which is modeled around the Froyd et al. (2000) "Organization Change Model" based upon the Kotter (1995) eight-step model for organizational change, is presented. The model includes the work of de Graaff and Kolmos (2007) and Daft (1978) regarding a dual focus on curriculum and organization in the change process.

2.1.1. ORGANIZATION CHANGE MODEL

Froyd, et. al., (2000) proposed the Organization Change Model as a model to transform undergraduate engineering education It focuses on organizational change and is based upon the eight-step change model developed by Kotter (1995). Table 2.1 shows the parallel steps for the Froyd and Kotter models.

Table 2.1. Organization Change Model

Froyd	Kotter
Establish need and energy for a curricular change	Establishing a Sense of Urgency
Gather a leadership team to design and promote the curricular change	Forming a Powerful Guiding Coalition
Define and agree upon new learning	Creating a Vision

objectives and a new learning environment	
Discuss the new objectives and environment with the college and revise based on feedback	Communicating the Vision
Implement new curriculum using a pilot, if necessary	Empowering Others to Act on the Vision
Conduct a formative evaluation of the program, investigating strengths and weaknesses of the current implementation, and indicators of short-term gains	Planning for and Creating Short-Term Wins
Decide how the new approach may be used for the entire college, and prepare an implementation plan	Consolidating Improvements and Producing More Change
Prepare faculty and staff for the new implementation, implement, and follow up with improvements	Institutionalizing New Approaches

The Organization Change Model primarily focuses on "changing people's attitudes toward ongoing curriculum change and equipping them to continually change. Its focus is on people rather than validity" (Froyd et al., 2000).

In this Organizational Change Model, "the underlying assumption is that the need for change must be well established and nurtured before the rest of the process can succeed (Froyd et al., 2000). Establishing the need for change is a very important step in the change process. The literature on change contains many references to this. Kotter (1995) identifies allowing too much complacency as the first error causing organizational failure and identifies creating a sense of urgency as the first step in a successful change process. It is critical that the sense of urgency be recognized at all levels within the organization.

Kezar's (2001) six categories for change also focus on the urgency for change and are based on a "distinct set of assumptions about why change occurs." The strategies all focus on what causes people and education institutions to change, and then use that information to guide the change process. In Graham's Royal Academy of Engineering and MIT commissioned report, Achieving Excellence in Engineering Education: The Ingredients of Successful Change (Graham, 2012a), the first common feature of successful programs of change is that it requires it to be about the entire curriculum structure and created interconnectivity across the structure of the program. This requires the entire organization to recognize the urgency and to coherently support the change being attempted.

In the development of the Organization Change Model, Froyd (2000) gives three reasons for establishing the need and energy for change, the urgency. First: addressing the question "why change?" and also identifies that getting others to join in the sense of urgency is critical to gaining support for the change. Second: faculty members need to believe the innovation will be successful before bringing it to the classroom. They have great influence over students' motivation, which is critical to a successful change process. Third: as faculty members embrace the change, they "may spontaneously work to improve their learning environments." Identifying the drivers for creating this urgency and establishing the need and energy for change is a critical first step in the change process. "Change in learning will only occur if there are both external and internal drivers" (Kolmos, 2013).

The second step in the change process is forming a leadership team and promoting the curricular change. This guiding coalition will need to include members of all levels at an institution: administration, faculty, and staff who are convinced of the need, as well as the skeptics. Kolmos (2013) also highlights the inclusion of individuals from all levels to create a top-down and bottom-up approach as a critical part of creating adequate internal drivers and core change agents. Additional engineering education literature supports the combination of top-down and bottom-up approaches for successful educational change (de Graaff & Kolmos, 2007; Heywood, 2006; Seymour, DeWelde, & Fry, 2011; Walkington, 2002). Berglund, Ritzén, and Bernhard (2014) identify the need for a balance support of the change between the two approaches. In their review of organizational change, the identify the increased sustainability of change when it is accomplished through a wide, program-level context. Kolmos (2013) also identifies that importance of educating the core change agents and the potential for inspiration by engaging other regional and international education communities in the process.

Steps three, four, and five focus on vision casting and communicating, and then empowering people to act on that vision. Fullan (2001) and Moesby (2004) identify vision and consensus as key internal drivers needed for successful change, and yet they are often missing in most engineering educational changes (de Graaff & Kolmos, 2007). Three of Kotter's (1995) eight reasons for firms failing involve vision:

- Underestimating the power of vision
- Under-communicating the vision by a factor of 10 (or 100 or 1000)
- Permitting obstacles to block the new vision

Froyd's model identifies that vision creation, communication, and implementation all need to focus on curriculum development in the engineering education change process. It is imperative that the vision is supported by, and addresses, the drivers for change. It is not adequate for the vision casting and communication to come from just one level of the organization, empowering people to act means empowering people at every level of the organization. Graham (2012a) identifies the importance of "strong leadership with a clear and well communicated educational vision" as one of the key features of successful change. In discussing this, Graham quotes both Kezar (2009) "one of the main reasons that changes do not occur is that people fundamentally do not understand the proposed change and need to undergo a learning process in order to successfully enact the change" and Seymour et al. (2011) regarding the importance of "radicalized seniors" serving as key champions in the change process "in publicly promoting educational improvements, legitimating their uptake, protecting younger faculty reformers from negative consequences of their work, and using their power and influence to leverage change at the national, institutional, departmental, and disciplinary levels".

De Graaff and Kolmos (2007) also identify the need for all levels of the organization to be involved if the change is going to be successful. Both a top-down and bottom-up strategy must exist such that the different organizational level efforts are complementing one another in developing a common vision. Ownership at all levels is necessary for all levels to be drivers for change (Kolmos, 2013). Engaging all levels of the organization is about creating a sustained institution movement. Change is a process, not an event (Fullan, 2001).

The initial vision will need to be evaluated and improved upon in an iterative process. The sixth step is about formative evaluation of the new curriculum with the purpose of understanding what needs to be improved and, equally important, celebrating what are the initial successes. Doing so will address two of Kotter's (1995) other reasons for firms failing. First, they fail to create short-term wins to keep people excited about and engaged in the new curriculum, and secondly, they declare victory too soon, which would allow complacency from some individuals to see, and for the naysayers to be able to point out, its shortcomings before the model is fully developed. Again, the change process is about creating a sustained institutional movement.

Steps seven and eight are about anchoring the change in the culture of the institution. This is a critical step in the change process (Kotter, 1995). Froyd's, (2000) premise for the model is about "changing people's attitudes toward ongoing curriculum change and equipping them to continually change." It is important to not only make this change part of the culture of the campus, but it is more important to use this process to create a culture focused on continual positive change. Graham (2012a) identified that the successful program changes in her study are ambitious and aspire to develop a new "brand for the education(al) approach". The aspect of creating a national or international educational model is a motivating factor in the engaging the faculty and creating a sustained institutional movement.

In summary, Froyd's Organization Change Model provides a model for the transformation of an engineering educational curriculum at an institution by focusing on changing peoples' attitudes and creating a culture of change. Utilizing this model requires an understanding of what the focus will be in the vision for the engineering education curriculum change process to developing the sustained institutional movement.

2.1.2. CURRICULUM MODEL FOR CHANGE

Daft's (1978) work on organization change led to the dual-core model of organizational innovation which recognized the need for both a technical and an administrative core in the focus of the change process. The technical core is the operational level of an organization, which, in education, would parallel the curricular level of focus for development. The administrative level in an educational institution includes the structure, policies, procedures, and culture created by the campus leadership.

De Graaff and Kolmos (2007) in "Management of Change" introduce a curriculum model for engineering education that identifies relevant elements for a successful change. It is based on findings and works of Him and Hippe (1993) and Kolmos (2002) with relationship didactics modeling. Like Daft's model, it focuses on two layers, the curriculum layer and the organizational layer. The *curricular layer* is focused on six elements: 1) students, 2) teachers, 3) goals, 4) selection of contents, 5) teaching and learning methods, and 6) assessment. The *organizational layer* is focused on 1) organization and culture, 2) values and conceptual change, and 3) physical space and resources. This curricular change model is pictured in Figure 2.1.

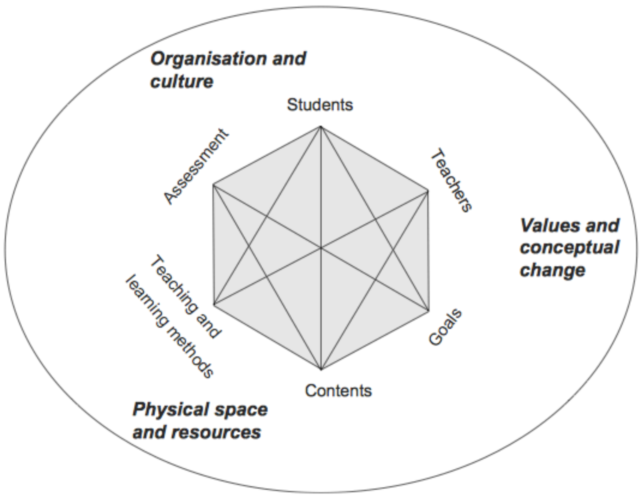


Figure 2.1. Curriculum model for change (de Graaff and Kolmos, 2007)

This model does not define the process for change, but when used in conjunction with Froyd's Organization Change Model, provides a deeper understating of the elements and actors who need their own process of development. The development process and support for the change vision will be strengthened by purposefully addressing each of these in the change process.

2.1.3. CONTRASTING OF PROPOSED MODELS WITH OTHER MODELS FOR CHANGE

Effective utilization of the Organization Change Model and the Curriculum Model for Change require an understanding of what other models could have been used and were not chosen for this work. In the proposal for the Organization Change Model, two other models for engineering curriculum change are identified and evaluated by Froyd, et. al. (2000). The first is described as the "current change model." It is the process used by most faculty members in higher education and is composed of the following steps:

- "Recognize dissatisfaction with an element of their students' performance or participation levels.
- Do an informal search for a solution.
- Choose and implement one or more curricular or pedagogical changes to address the problem.
- Gather informal feedback on the success of the innovation, e.g., observing students' reactions and asking for students' comments.
- Decide whether or not to continue using the innovation, and if a decision is made to continue, decide how to modify the implementation."

Froyd (2000) identifies three reasons this "current change model" will not create the needed widespread transformation:

1. Lack of sufficient rigor required to convince skeptics.
2. Motivation arises from individuals' dissatisfaction, and others who don't share the same dissatisfaction and "vision, beliefs, or values" will be unlikely to adopt.

3. Faculty members act alone, and research shows sustained change is more likely to happen when innovation occurs through a coalition of committed faculty.

Curricular changes from this approach are also often very narrow in scope and generally focus on a single course or set of courses and what a student should "know, understand, and be able to do" (Blackmore & Kandiko, 2012). It doesn't appear that these processes are capable of creating the transformation of engineering education needed to meet the new wave of innovation and technology challenges that graduates will be encountering. The 2013 UNESCO Report on engineering education concurs "there is almost a total lack of action by universities to realize the essential transformation" (Beanland & Hadgraft, 2013). Froyd identifies that if transformation in engineering education is to occur, it is necessary to move past this slow state of incremental change in the U.S. education system toward a model that meets the called for changes. Graham (2012a) also identifies the limited success and meaningful impact of this approach to change.

The second model is the "Espoused Change Model." It has been promoted as a model for facilitating this change and is based mostly upon the scientific method. Froyd (2000) identifies it as the model promoted by many organizations that fund engineering education transformation efforts (including National Science Foundation, NSF) and faculty members themselves. It is based on the following steps:

1. "Conceive curricular change aimed at improvement.
2. Pilot a new curriculum to test the idea.
3. Assess and evaluate results.
4. Adopt, if supporting results support change" (Froyd et al., 2000).

The underlying assumption is that other engineering faculty will be convinced by the results of these studies and look to implement changes in their courses and curriculums. Again, the evidence shows that this method is not creating the change needed in the engineering education system, especially in the U.S.

Another set of strategies that can be identified for change come from the work of Bennis, Benne, & Chin (1985). They propose three strategy categories for change. They also have shortcomings in creating a model of change, but they are important to identify and recognize, as they are also models commonly used in change processes. They have key aspects that will need to be considered as a new model for an engineering curriculum is developed.

The first category is "empirical-rational strategies." These strategies assume that people are rational individuals who are interested in personal gain; and, if an advantage is pointed out to them, they will make the change to gain this advantage. It is the strategy at the heart of the current change model and the espoused change model described by (Froyd et al., 2000). Empirical-rational strategies are limited in that what is advantageous for the institution may not be beneficial to an individual faculty member. In fact, innovations in engineering education could threaten to diminish the job satisfaction of faculty members who employ already established engineering education methods (de Graaff & Mierson, 2005). This reason is cited by the Royal Academy of Engineering in the 2012 "Achieving Excellence in Engineering Education: The Ingredients of Successful Change" as one of the main barriers to engineering education reform, especially in countries like Germany and the US, where the professor has great control over curriculum. In contrast, countries such as Denmark and Australia are identified for their greater potential to transform engineering education, due to the greater control that administration or campus leadership has over the curriculum (Graham, 2012a). Although these strategies may not produce the desired change in engineering education, the aspect of creating a framework that allows individual faculty members to create rational changes from their own individual perspective in a way that supports the overall desired engineering curriculum transformation of the institution is an important requirement of the change process.

The second category consists of the "normative-re-education strategies," which assume that people are conservative in nature and places emphasis on the social aspects of human behavior. The main focus is changing the value system of an institution to achieve desired results. The importance of changing the patterns of values and attitudes for the majority of individuals is emphasized as a critical aspect of the change process. This creates a higher acceptability of new ideas that is critical for the success of the Organization Change Model and the institutionalizing of the new curriculum. The challenge of these strategies is the lengthy time they take, which can result in the need for the short-term wins Kotter identifies as necessary for successful change.

"Power-coercive strategies" form the third category, and they assume that a top-down approach is needed because individuals will not recognize the advantages and risks for the entire organization. These strategies are effective in serving the needs of quick visible results for the most urgent of issues, but will have few long-term effects, as the initiative rests with a small group of individuals. Clearly, the long-term nature of engineering education transformation poses a challenge for such strategies. However, they can serve an important part in the initiation of engineering education reform at an institution (de Graaff & Kolmos, 2007) within the initial stages of the Organization Change Model.

Aspects of these other models, with which individuals may be more familiar or comfortable using, will need to be addressed as the institution navigates this complex change process and tries to avoid the major dilemma described by Cyert and March in their study of organizations: “The major dilemma in organization theory has been between putting into the theory all the features of organizations we think are relevant and thereby making the theory unmanageable, or pruning the model down to a simple system, thereby making it unrealistic” (Cyert & March, 1959).

2.1.4. CONCLUSION

Change, on the order of developing a new engineering program, is a complex and difficult process. The reality of such a complex level of change cannot be captured by one model. Success requires the use multiple models of understanding change and then using them to guide the process. For this study, the Organizational Change Model will guide the overall process. It will be incorporated with the dual layers and elements from the Curriculum Change Model to provide a deeper understating of the elements and actors in the process of the new PBL curriculum development.

The structural focus of the change is creating common visions that engage all levels of the organization such that the organization creates a genuine sustained institutional movement. In subsequent sections and chapters, the potential curricular and learning theories for the new engineering curriculum will be developed to define the curricular and organizational elements for the Iron Range Engineering program. This theoretical framework on change will be used in Chapter 3 to analyze the development of the IRE PBL program.

2.2. CURRICULAR THEORY

With the background of change perspectives in place, the next step is to address the curriculum. In this section, curriculum is considered from three viewpoints. First, from a perspective of curriculum in practice, the structural elements are described and arranged in a model. Second, from the literature, a classification framework is presented for use. Third, exemplary practices for the future of engineering curriculum are presented. The outcome of the section is an extensive set of criteria to be used in Chapter 4 to address the objective to *show how the curricular elements of the IRE model are implemented* and to analyze the curriculum from these theoretical perspectives.

2.2.1. CURRICULUM FROM PRACTICE PERSPECTIVE

The curriculum arises to meet the needs of the profession, which includes the profession meeting the needs of society, and the needs of the whole student. The curriculum can then be seen as a compilation or organization of the courses. Crucial to the success of the curriculum is the greater environment in which it is enacted (Barnett & Coate, 2004). Moving down one layer, there is an outline of learning for each course and the environment and enactment of the course. An ultimate goal is to achieve student-learning outcomes that provide them with the tools to meet their own needs and those of their profession, essentially closing the loop from outcomes back to original requirements.

There are many different perspectives that one can assume on curriculum from the perspective of practitioners in higher education. Figure 2.2 shows a model of increasing levels of sophistication. The simplest view would be to consider a program's curriculum as a set of courses. For example, the engineering program curriculum consists of calculus, physics, engineering science, engineering design, etc.

Next would be to consider the courses in combination with objectives for the program. An example of a program objective would be "graduates will be capable of designing, implementing and integrating thermal, electrical, mechanical, and computer-controlled systems and processes that will serve the region, the nation and the world within one to four years of graduation." This is a program objective of the Iron Range Engineering program (ire.mnscu.edu/about-ire/objectives.html, 2016).

Beyond looking at curriculum as a set of courses and objectives, one must consider the design and instruction of the courses as part of the curriculum. Further, one must consider the curriculum from the standpoint of why it exists. For engineering, a viewpoint could be that the curriculum exists to meet the needs of the profession, and in turn, meet the needs of society. For example, Dreher and Kammasch (2014) set a benchmark for engineering education in proposing the Leonardian Oath. Similar to the Hippocratic Oath for medicine, the Leonardian Oath would have curricular outcomes focused on ethical responsibilities such as sustainability and economic impact.

When we graduated with engineering degrees in the 1980's and 1990's, the programs operated under this viewpoint of curriculum. The goal was to complete a set of courses, designed and delivered in a homogenous lecture-laboratory-homework-exam format. Upon graduation, it was expected that we would go and meet the needs of society.

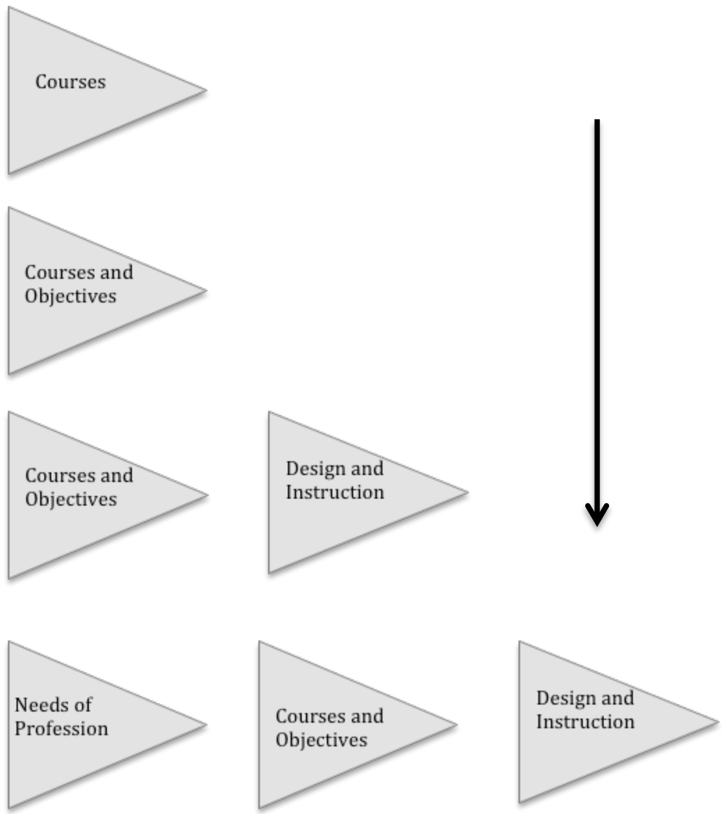


Figure 2.2. Increasingly sophisticated views of curriculum

In the late 1990's, the concept of student outcome in engineering education emerged in the United States (www.abet.org/about-abet/history). In so doing, it added a layer of sophistication. In addition to graduating and being expected to meet objectives to serve society, explicit details were made visible about what skills and competencies the students should have acquired by graduation (ABET a-k). Further, feedback mechanisms within the curriculum became standard. The levels to which students meet the outcomes were assessed and the results fed back to the set of program courses and the design and instruction models. This is the view of engineering program curriculum most commonly held in the U.S. today (ABET 2015). See Figure 2.3.

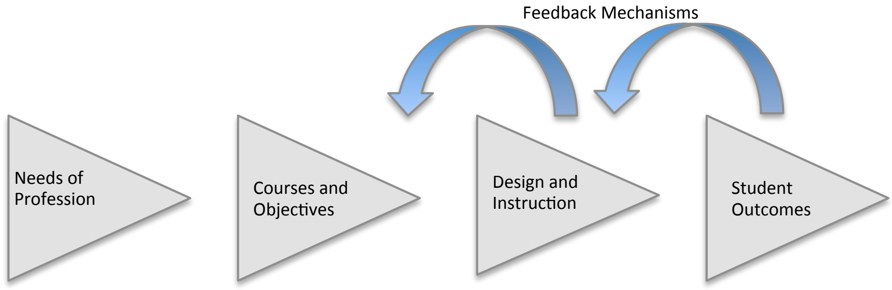


Figure 2.3. Current view of engineering education curriculum in U.S.

Student Outcomes can be identified as both intended student outcomes, those that the curriculum designers would want students to attain, and as actual student outcomes, those that the students actually acquire as a result of their whole experience in the curriculum (Joachim Walther, Kellam, Sochacka, & Radcliffe, 2011).

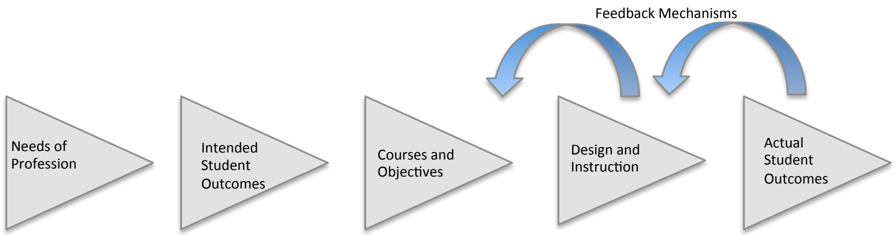


Figure 2.4. Recognizing the difference between intended and actual student outcomes.

Barnett and Coate (2004) proposed that in addition to curriculum being considered as a set of courses and objectives, curriculum is something that is enacted. The delivery of the curriculum in terms of environment and community would play an impactful role in how a curriculum is instituted. To give an example, the Iron Range Engineering program grew out of the Itasca Community College two-year engineering program in Grand Rapids, Minnesota. The list of courses/objectives and model of teaching at this college is very similar to that of other community colleges in Minnesota. However, the student experience of the curriculum is drastically different. The level to which students build identity and achieve success, as impacted by their learning environment and learning communities, is substantially higher (Johnson & Ulseth, 2011).

Beyond Barnett's assertion that curriculum is enacted, as practitioners, we propose that courses are also enacted. As an example, in Spring 2013, the two authors each taught a first-year level physics/statics/engineering design course. We had similar philosophies and followed the same course outlines. Yet, our students' experiences were vastly different. The differences were caused by the different ways in which we enacted the courses, the different stories we told, the different concepts we emphasized, and the different learning activities in which we had our students engage.

Further, just as the curriculum should be designed to meet the needs of the profession and society, it should be designed to meet the needs of the whole student. Figure 2.5 shows a curriculum model that includes meeting the needs of the profession as well as the student, where the program curriculum is a set of courses and objectives that are enacted; where the courses are designed, instructed, and enacted; where there are intended and actual student outcomes; and where there are feedback loops in place for continuous improvement and evolution.

The bordered box identifies the actual student experience. To the left of the student experience are the inputs and to the right is the outcome.

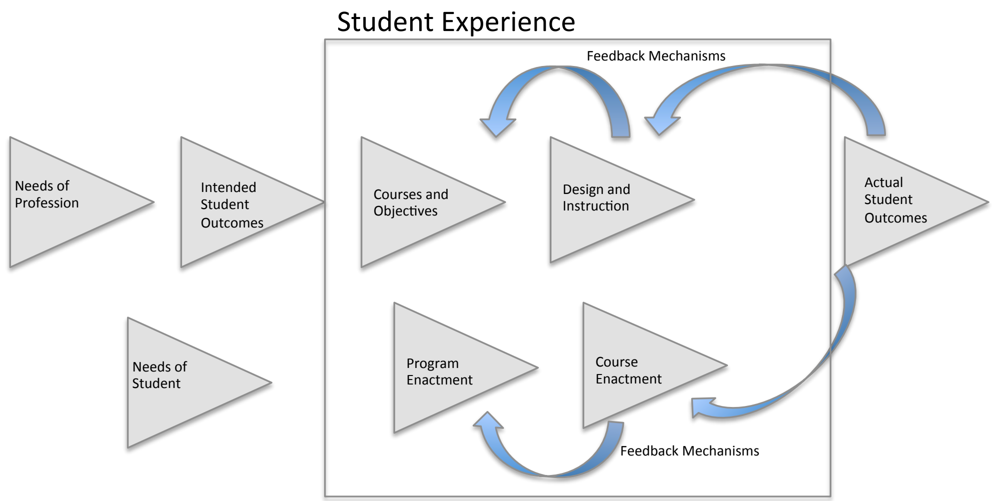


Figure 2.5. Practitioner's view of curriculum

2.2.2. CURRICULUM CLASSIFICATION

There is relevant recent literature regarding the development and implementation of engineering curriculum: Barnett & Coate (2004), Jamison, Kolmos, & Holgaard (2014), Sheppard et al. (2009), Cowan (2006), Rompelman & de Graaff (2006), Kolmos and de Graaff (2014), and Beanland and Hadgraft (2013). Following is an overview of these relevant contributions and connections of these works to one another.

Barnett and Coate (2004) present a classification continuum from knowing to acting to being. Knowing is aligned with the accumulation of knowledge. It brings to mind derivations, theories, information. This classification would be aligned with an emphasis on lecture and developing algorithms to solve closed-ended problems. Jamison et al. (2014) describe this as the ideal of the polytechnic model, or the "scientific university," where thinking is prized over doing. Most traditional engineering programs fall under this classification.

Acting is the "doing" of engineering. It is learning to engineer by practicing the way engineers will practice in the profession. Cooperative "co-op" experiences or internships in which students are immersed side-by-side with practicing professionals would be an example of this classification. Jamison, Kolmos, and Holgaard classify this model as a market-driven approach or as the "entrepreneurial university." Here, a wider spectrum of skills and abilities are valued. In addition to technical acumen, abilities to design, communicate, lead, invent, and overall become a practicing professional are the attributes desired in the graduates.

"Being" brings out the humanistic aspects of engineering. It is using the talents of the engineer to solve problems for people, the environment, and society. Activities such as Engineers Without Borders (www.ewb-international.org) and "designing for sustainability" are aligned with being. Jamison, Kolmos, and Holgaard label this as a social and cultural orientation and term the programs as being from the "ecological university." The individual brings civic engagement and responsibility to the community as higher-level values to their practice.

While the Barnett and Coate classifications of knowing, acting, and being are presented above as discreet, they are more of a continuum. In-place curricula around the world differ in the various emphases put in each of these areas. In any space where one of the values is placed above the other two, such as KNOWING-acting-being; knowing-ACTING-being; or knowing-acting-BEING; the curricula could be so classified, and then flavored by the other two. Beyond knowing-acting-being, Jamison, Kolmos, and Holgaard propose a model of Hybrid Imagining, a place where all three areas are equally valued. This would be a concept of KNOWING-ACTING-BEING. They imagine a future in which this model could be the ultimate goal of curricular design in engineering education.

These conceptualizations arise in the perceived needs of the profession/society. Curriculum designers have to interpret these needs and their place along the continuum. These interpretations, along with any externally imposed mandates, such as by accrediting agencies, then lead to the development of the intended student learning outcomes. The actual student-acquired outcomes will be the results of how the courses are designed, how the instruction is designed, how the courses and instruction are enacted, and the level to which feedback is used in the processes to influence continuous improvement. In some cases, there will be close alignment along the knowing-acting-being continuum of what was intended and what the graduates acquire. Sometimes, there will be poor alignment. For example, ABET requires that its accredited institutions have a fixed set of intended student learning outcomes, the ABET a-k. These outcomes could be classified as KNOWING-ACTING-being. Five of the outcomes are more technical, six of the outcomes are more professional, and only a few are tangentially societal. Thus, graduates of ABET-accredited engineering programs should have nearly equally high levels of technical and professional competence. However, course and instruction design and enactment lean much further toward the technical development (Sheppard et al., 2009). Graduates acquire KNOWING-acting-being attributes. This misalignment is an example of a major source of the calls for reform that were summarized in Section 1.3.

In the coming presentation of future models of curriculum, we will classify using the knowing-acting-being from Barnett and Coates and the polytechnic, entrepreneurial, ecological, hybrid imagining from Jamison, Kolmos, and Holgaard.

2.2.3. EMERGING MODELS OF CURRICULA

Spiral-Networked Model

Sheppard et al. (2009) present a "spiral-networked" curriculum model aimed at preparing graduates to be life-long learners. The spiral visually represents a circle of learning wherein fundamental principles of engineering are introduced on the first revolution, then used at higher and higher levels of sophistication on subsequent revolutions (see Figure 2.6).

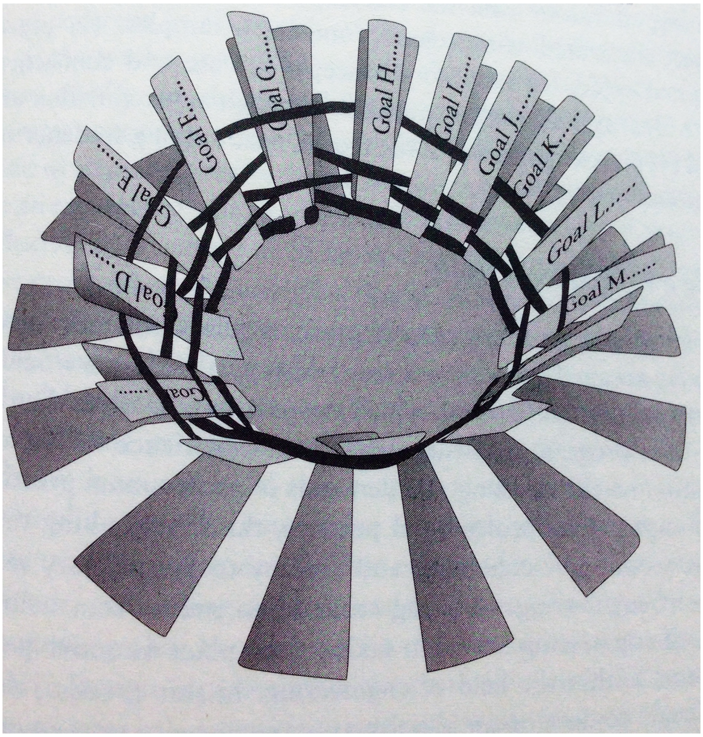


Figure 2.6. Sheppard networked component model (used with permission)

They propose that the learning is situated in activities that closely simulate those activities engineers undergo in professional practice. These activities develop the technical knowledge while developing the professional skills necessary for successful daily interactions in engineering practice. They also develop abilities that use the technical knowledge and professional skills to solve the complex engineering problems faced by engineers. Additionally, engineering students, as they traverse the spiral, would develop the identity and attitudes that allow them to react dynamically to change and persist toward solutions.

The visual model of the spiral is further described to include movement back and forth between specific situations and basic engineering principles, giving students practice in grounding their new work in fundamental science. Continually increasing sophistication in subsequent revolutions would provide students with the ability move along the trajectory toward engineering practice.

These goals proposed by Sheppard are what the engineering student would look like at graduation and thus are the proposed actual student outcomes. The attributes of the spiral-networked model include: 1) a focus on professional competency development, 2) a focus on the use of fundamental principles and their interconnectivity, 3) environments similar to engineering practice, and 4) immersing students in the physical world and empowering them to make connections, doing so multiple times throughout their education.

The spiral-networked model would be classified as KNOWING-ACTING-Being with some attention given to building engineering identity, but little emphasis on the humanistic value of the profession. Jamison, Kolmos, and Holgaard would classify this model as having attributes of both the polytechnic and entrepreneurial university. The spiral-networked model fits with the practitioners' view of curriculum from Figure 2.5 in the ways that it addresses the needs of the profession, the intended outcomes of the graduate, and both the design and enactment of the courses.

The value of the spiral-networked model is in classifying the level of professional skill focus, emphasis on fundamental principles, immersion in real engineering environments, and degree of use of a spiral model in engineering curricula.

Systems Engineering

Rompelman & de Graaff (2006) apply a systems engineering approach to viewing a curriculum. They identify the system boundaries as encompassing the students, the teachers, and the interactions between students and teachers. Within this boundary, then, is the educational process. The inputs to the system are the educational objectives. The output is the student, including his/her attributes. Assessment is a key that empowers several feedback loops. Assessment of the abilities of the student output provides feedback to the input (objectives), feedback to the students in the system, and feedback to the teachers in the system. Summative assessment is also an output of the results of the system.

Rompelman and de Graaff follow their view of curriculum by taking an engineering designer's approach to building a curriculum. They define the need for a new curriculum as a problem to be solved, identifying a problem as a gap between what is and what is desired. Using standard design principles, they look at problem definition and criteria definition. This leads to a product requirements plan, development of solutions, simulation and evaluation of solutions, and selection of the best solution. Transferring the design approach of a product to the design of a curriculum, analogies are made. Desired outcomes become the problem definition. The product requirements plan becomes the course requirements plan. Solutions come in the form of choosing appropriate learning activities that are likely to align with desired outcomes. Evaluation is made to compare the viability of the different solutions options against the course requirements. Then, a final selection is made based on the evaluation.

The practitioner's view of curriculum shown above in Figure 2.6 is similar to the systems engineering model. Slight dissimilarities exist, in that the practitioner's view further breaks down the objectives into needs of the profession and needs of the student, and further defines the educational process to include the program and course design, program and course instruction, and program and course enactment.

This design-based approach of the systems engineering model highlights the need to address alignment of outcomes and instructional approaches. It will be used to classify curricular models based on the inclusion of a method to continuously monitor, through feedback mechanisms, the alignment of instructional methods with desired outcomes.

Project-based Learning

Kolmos et al. (2014) present PBL as a curriculum. They define three separate, yet interrelated PBL learning principles: learning, social, and contents. Learning includes problem-solving, ownership of problems, and organization of learning. Social is team-based with interaction between the individual and her or his group. Learning takes place through conversation. Students share knowledge and collaboratively construct it. Contents are the interdisciplinary fundamental principles of engineering, learned through an approach similar to that of a scientist conducting research or through other exemplary methods.

Through the PBL learning principles, alignment theory, and social construction theory, they identify 7 curricular elements to PBL: 1) outcomes, 2) types of problems and projects, 3) progression, size, and duration, 4) students' learning, 5) academic staff facilitation, 6) physical space and organization, 7) assessment and evaluation. From these elements, we have further methods for classifying curricula. Are problems or projects used and to what extent (courses or whole curriculums)? Is the student learning receptive or constructive? What level of facilitation training does academic staff receive? How is physical space allotted for learning? What levels of individual/group and formative/summative assessment are used?

PBL includes all of the aspects in practitioner's view of curriculum in Figure 2.6. There are intended student outcomes, aligned with instruction, aligned with actual outcomes. PBL is dependent on enactment at the course and program (curriculum) levels. Further, PBL has assessment and evaluation feedback loops to all aspects of the curriculum. Kolmos and de Graaff describe the motivations for PBL and show them as the needs of the profession for new engineering competences. The social requirements of PBL align with our view of the needs of the student. In summary, the principles of PBL and its phases of implementation align very well with our complete view of curricula. However, it is how institutions and individual faculty members enact PBL that will determine what kinds, and to what extent, actual needs are met.

The description of PBL as a curriculum can be connected to the previously discussed models and views. For Barnett and Coates, different institutions could enact PBL differently, to put emphasis on any of the different knowing-acting-being models. From Jamison, Kolmos, and Holgaard, the same could be said; depending on institutional enactment, emphasis could be on scientific, entrepreneurial, ecological, or hybrid imagining. However, by its nature, PBL leans toward engineering practice as seen in entrepreneurial, ecological, and hybrid imagining. From Sheppard, PBL curricula can be enacted in a spiral model, with a professional spine, with a focus on fundamental principles, and in an immersion in professional practice. By its nature, PBL integrates knowledge and skills in an approximation of engineering practice. From Rompleman and de Graaff, PBL is a curriculum that, by design, has alignment between outcomes and instruction. Similarly, PBL has feedback mechanisms to monitor the alignment.

2.2.4. ESSENTIAL CURRICULAR ATTRIBUTES

In addition to the models of curriculum presented above, two essential attributes to consider are reflection and identity building. In the upcoming section on learning theory, the important elements in the design of learning environments are described and synthesized. Reflection and identity are included in that discussion but, due to their critical importance, are first included in this discussion on the design of curricula.

Reflection

Reflection "is a vital and rigorous component of the learning process and a critically important part of the engineering profession" (Lima & Oakes, 2014). Cowan (2006) brings a new perspective to the aspects of curriculum previously discussed. This perspective is that of reflection in the learning process. Cowan presents three learning principles related to reflection and then presents a model for reflection.

Cowan's principles: 1) developing the ability to do something comes from examples, 2) people who think about "how" they do something will improve at doing it, 3) people who think about "how well" they do things and how well they "could do things," are more effective self-directed/managed learners.

These principles lead directly to Cowan's three-part model in which a learner reflects before learning, during learning, and after learning. Before learning is termed "reflection-for-action." The learner connects prior learning to what is about to be learned. The learner then plans for the learning to come by setting goals, organizing resources, and purposefully determining the rate and effort to be expended on the learning. During the learning, the second reflection, “reflection-in-action,” takes place. At this point, the learner recaps what is being learned and how it is being learned. The learner takes this time to ensure alignment between the goals and the learning activity as well as predicting the likelihood of success of the learning. Lastly, is reflection-on-action where the learner identifies the value of the learning, evaluates the quality of the learning, and describes how the learning will carry forward.

Cowan’s reflection model fits in the area of course enactment. The importance of reflection is embodied in the metacognitive aspects of learning. It happens at the content level in engineering education and at the intersection of the instructor and the student. Undergraduate students tend not to have developed this level of sophistication in their ability to become self-directed learners. Instructors need to convince students of the value of reflecting, model reflection for the students, and give them formative feedback on their reflective abilities. Left on their own, instructors will implement reflective practices with their students on a continuum of “not at all” to “quite well.” Therefore, if the development of reflective abilities is to be an actual outcome at graduation, it should be stated as an intended outcome in the development of the curriculum. Additionally, instructors should be given proper training in how to develop reflective abilities in their students. This would be evident in the program enactment of our view of curriculum.

To classify Cowan’s view of reflection among the previously discussed curricular aspects, reflection in the development of self-directed learning would be of high value in any of Barnett and Coate’s knowing-acting-being or Jamison, Kolmos, and Holgaard’s scientific-entrepreneurial-ecological-hybrid imaging classifications. Though, reflective practice could be more highly valued in the “being” and “ecological or hybrid imagining” models. The act of reflecting to connect prior learning to current learning, and connecting current learning to future learning, is evident in Sheppard et al.’s spiral model where learning goals are made explicit to students and monitored for alignment. Similarly with Rompleman and de Graaff’s model, reflection is key to feedback mechanisms ensuring alignment of learning outcomes with instruction. Kolmos and de Graaff’s model of PBL has, as a key component, both individual and team reflection. For further classification purposes, we will identify to what degree curricula include reflection as a priority for student learning and outcomes.

<u>Identity</u>

Dehing (2013) identifies the importance of identity building as a component of engineering curricula. They point out that the value of professional identity building is to increase motivation for student learning and make the connection that students with higher professional identity develop higher learner maturity, becoming more self-directed learners. They define professional identity as having two dimensions.

There is a social dimension in which the individual “acts” like an engineer by meeting the requirements of the profession. There is also an individual dimension in which the person feels like an engineer, as displayed through their definition of themselves regarding beliefs, values, attributes, and motives.

Dehing, et al., further describe the attributes of a curriculum that lead to the development of professional identity in engineering students: 1) have identity development as an explicit goal of the curriculum, 2) treat students as “student engineers” from the beginning of their education, 3) align the curriculum with the professional practice of engineering, 4) provide a presence of practice professionals for mentorship, 5) ensure that teaching faculty have a shared and explicit view of professional behavior.

To align identity with the practitioner’s model of curriculum: place identity building as an intended student outcome, consider the alignment of professional practice and presence of practicing professionals a part of the curricular design, and place having teaching faculty develop shared/explicit view of professional behavior in program enactment and course enactment. Professional identity building aligns with Barnett and Coate’s as knowing-ACTING-being and with Jamison, Kolmos, and Holgaard in the entrepreneurial university and in their hybrid imagining. Professional identity building is central to Sheppard et al.’s spiral model of developing the future engineering professional. Kolmos and de Graaff’s PBL model lends to the development of professional identity through the action of students practicing engineering throughout the entire curriculum and the use of physical space to provide a place for engineering practice.

2.2.5. CURRICULAR TRANSFORMATION

Beanland and Hadgraft (2013) utilized 15 contributing panels to publish the UNESCO Report, Engineering Education: Transformation and Innovation. They first made a case for transforming engineering education, then provided a model for transformation, finishing with a look at how to make transformation happen. This model for transformation serves to tie together much of the works discussed above.

Beanland and Hadgraft identify that transformation should occur in regards to curriculum structure and content (design) as well as in program delivery (enactment) and assessment (feedback). They produce 6 key steps to guide the design and implementation of engineering curricula: 1) adopt Washington Accord attributes (actual outcomes), 2) maximize development of capabilities essential to engineering practice (actual outcomes), 3) first-year experiences designed and enacted to maximize student motivation (design and enactment), 4) use PBL in each year (design), 5) replace lecture with student learning (enactment), 6) use wide range of IT and communication systems to facilitate student learning (enactment).

Further, the report makes the following arguments (where appropriate, relevancy from the works listed above is shown in parentheses):

- "It is suggested that engineering students should be treated as trainee engineers and confront engineering issues from day one of their program" (spiral network, identity building)

- "… engineering projects are the vehicle to:

    - introduce breadth of engineering understanding in early years
    - develop motivation and commitment to engineering
    - develop communication skills
    - introduce ethical and social responsibility and business dimensions of engineering
    - address the sustainability of engineering projects
    - require innovation in the realization of solutions
    - develop specialized knowledge in capstone projects."

  (PBL, spiral network, identity building)

- "It is not desirable nor effective to build the program around a series of ineffective, and consequently inefficient, lecture presentations when the alternative exists to use a project-based program to create student-centered learning which is consistent with the development of the desired engineering graduate attributes. This is the core issue. It is the key to transformation. It requires major change." (PBL, spiral network, identity building, systems engineering)

- "To seriously promote student-centered learning a dedicated home-room, which provides an engineering project office-like environment, is required." (PBL)

- "Students and academic staff work together to monitor and record the progress toward achieving specified learning outcomes to optimize the effectiveness of student learning…" (reflection, systems engineering)

The report concludes with 24 elements that are key to the transformation. The following are highly relevant to this discussion on curriculum listed with the germane discussion models from above:

4) Curricula should be implemented using project-based pedagogies (PBL)
7) Curricula should be focused on providing personal learning experiences aimed at developing engineering practitioners (spiral-networked, PBL)
9) Outcomes should include the development of attributes essential for the practice of engineering (engineering systems, PBL, identity)

13) Teaching faculty should facilitate personalized student learning through the use of student-centered learning activities (PBL)
17) Physical learning spaces need to be altered to accommodate project-based and student-centered learning (PBL)
23) Engineering employers should form effective partnerships with learning institutions to empower the transformation (identity)

In summary, the UNESCO report calls for transformation in engineering education and does so by proposing many of the curricular components that are addressed in this section.

2.2.6. FRAMEWORK FOR CLASSIFYING

The synthesis of the curricular components provided above results in a framework for analyzing an engineering curriculum. The framework is presented below as series of questions. The answers to the questions classify according to its attributes in regards to its intent, design, and enactment.

Curriculum Classification

Is there a higher emphasis on knowing, acting, or being? Or are they valued equally?
Is the program scientific, entrepreneurial, or ecological? Or hybrid imagining?

What are the intended student learning outcomes?

To what level do they align with the Washington Accord?
To what level is instruction aligned with outcomes?
To what level is enactment aligned with outcomes?
Is identity building an intended learning outcome?

Are intended learning outcomes realized as actual student outcomes?

Is there a continuous feedback system to ensure alignment of intended outcomes, instructional design, program enactment, and course enactment with actual student outcomes?
To what level is the alignment achieved?

Are the needs of the student addressed in the curriculum design and enactment?

To what level is motivation for student learning considered in the design and enactment of the curriculum?
To what levels are students included in the decision making of learning activities?
To what levels do faculty involve students in analyzing their progress in achievement of their learning outcomes?

Does the curriculum design/enactment align with exemplary practice?
To what level does the curriculum align with professional practice?
Is PBL used? To what level?
To what level does the curriculum have and enact a professional spine?
Where does learning fall on the continuum of lecture/receiving to student-centered/active/constructive?
How is physical space allotted for student-centered learning?
How is assessment conducted?
(Formative/Summative?, Individual/Group?)
To what level are students treated as student engineers?
To what level do teaching faculty share and explicate a common view of professional practice?
To what level are students exposed to practicing professionals?
Does academic staff receive training in facilitation?
To what level is reflection used in student learning?
Are students given feedback on their reflective abilities?
Are academic staff trained in giving feedback on reflection?
How are fundamental principles interconnected with each other and engineering practice?
Is a spiral model implemented for the learning of fundamental principles?

Figure 2.7. Framework for classifying engineering curricula

The UNESCO report states "…curriculum is a multi-variable complex engineering problem. It does not have a unique solution, but it does have some essential elements…" Multiple perspectives of engineering curricula have been presented and related to one another in order to develop the above classification framework. The framework, when applied to an existing or new curriculum, can paint the picture of that unique curriculum. The framework consists of over 25 questions. Most of the questions have answers that are on a continuum from low to high. In Chapter 4, this framework for classifying curricula is used to classify the Iron Range Engineering curriculum to further address the objective to *show how the curricular elements of the IRE model are implemented.*

2.2.7. CONCLUSION

In summary, we have presented curriculum theory from a variety of perspectives. First we developed a look of curriculum from the point of view of engineering education practitioners. Next, we discussed curriculum classifications. Third, we analyzed emerging curricular models. Finally, we detailed two essential curricular elements. All of these perspectives were synthesized into a framework for classifying curricula. The framework is a set of many questions, the answers to which create a unique "fingerprint" of that curriculum, enabling it to be described and compared to others.

Key Finding: ***This framework will be applied to analyze the Iron Range Engineering model in Chapter 4. It also creates a taxonomy for classifying any PBL curriculum. As PBL is implemented more widely, it provides a "common language" for comparative discussion in understanding what individuals involved with curricular change aspire to accomplish with a PBL curriculum.***

2.3. LEARNING THEORY

The curricular theory discussion in the previous section covers a broad set of aspects. This section on learning theory focuses on one of the most critical of those aspects. To give an analogy, if curriculum were compared to a person's house, including their front yard and back yard, learning, then, would be an important room in the house such as the kitchen or the family room. PBL is a learner-centered pedagogy. Our motivations to start the IRE program and undertake the PhD studies are learner-centered. Thus, learning theory has become an important focus of study and is essential to address the objective of *analyzing the Iron Range Engineering program through theory.*

Following is a development of learning theory and design of learning environments using relevant literature. Illeris (2007) presents a framework for learning that serves as a model through which learning theories and aspects of a learning environment can be viewed in regard to their contribution to the learning process. We start by describing Illeris' model (2007) and then use Bransford et al. (2006) and Bransford, Brown, & Cocking (2000) to give validation to Illeris' model. Next, we present a discussion on constructivism as the primary theory of learning on which modern views of best practice are built, and include the American Psychological Association's learner-centered psychological principles while placing these in Illeris' model. This is followed with a literature-based description of the following relevant elements of learning and learning environments: development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity. We will describe each, discuss their relevance, and position them in the models of Illeris and their connection to the APA principles. Finally, we present a synthesis of this work to build a framework from which we will be able to apply to the Iron Range Engineering model analysis in Chapter 4.

2.3.1. ILLERIS MODEL OF LEARNING

Knud Illeris developed a forward-looking model of learning that allows a conceptualization of the different tensions that impact learning. His motivation was to develop a concept of learning that accounts for the complex acquisition of the wide range of competences that encompass traditional knowledge and analytical skills, overview capability, life skills, professional responsibility, and attributes such as flexibility, dynamism, creativity, leadership, and more (Illeris, 2003). He goes on to state that for any learning to take place, there must be two basic processes in play: internal interactions involving the psychological process of acquisition and elaboration, and external processes of interaction between the learner and his or her social, cultural, and physical environments.

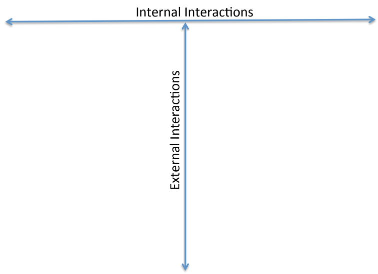


Figure 2.8. Two processes of learning (adapted from Illeris, 2007)

Illeris (2007) identifies three dimensions of learning. These are content, incentive, and interaction. The content dimension refers to the competences of knowledge, skills, and understanding. It is in this dimension that learning is acquired. It is the development of cognitive ability. The second dimension is incentive, wherein the motivations for learning are considered. In a simplistic view, if we consider the content dimension to be *what* is learned, the incentive dimension would be *why* the learner wants to learn and takes into account the emotions of learning. The third dimension considers the interactions that take place during the learning: the interactions between the learner and her learning community, and those between the learner and her environment. This is the social aspect of learning and could be considered part of the *where* and *how* the learning takes place. Illeris places these three dimensions of learning at their appropriate points on the ends of the process lines. See Figure 2.9 below.

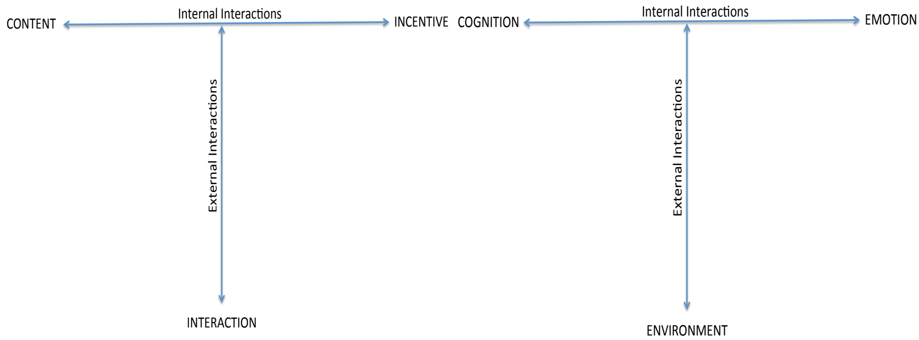


Figure 2.9. Illeris dimensions of learning

The content dimension is annotated by cognition, meaning, and functionality. Incentive is further described by emotion, sensitivity, and mental balance. At the top edge of the triangle, the leg between content and incentive is about the individual acquiring knowledge. When moving down toward sociality, the interactions between the student and the environment are considered.

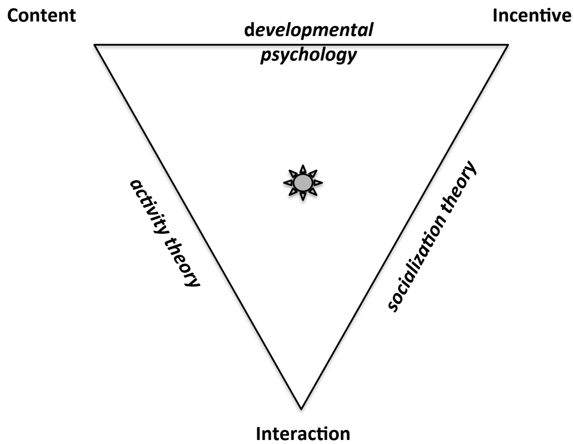


Figure 2.10. Illeris triangle (2002)

Illeris' theory is that learning takes place at the intersection of content, incentive, and interaction, or near the centroid of the triangle. Also, in Figure 2.10 Illeris labels the legs of the triangle with the relevant theories of learning where developmental psychology lies between the cognition and emotion vertices, socialization theory between emotion and society, and activity theory between cognition and society.

Beyond the three dimensions of learning, Illeris describes four types of learning: cumulative, assimilative, accommodative, and transformative. Cumulative learning takes place when the learner is entering the domain for the first time and has no previous mental frameworks on which to build the new learning. Assimilative learning takes place when previous learning has occurred when there are mental structures on which to build as new information is received through sensory input. Accommodative learning takes place through mental processes such as reflection, where the learner restructures mental models from one conception to another. Transformative learning can be viewed as a "complex accommodation involving the simultaneous restructuring of several cognitive as well as emotional schemes" (Illeris, 2003). He further indicates that transformative learning takes place in times of crisis when the individual is confronted with the need to quickly overcome a situation that exceeds her previous knowledge structures.

In the Cambridge Handbook of The Learning Sciences, Bransford et al. (2006) present three recent major insights on the understanding of learning and thinking:

1) The extent to which local cognition and social ecology can support or constrain learning.
2) Importance of social aspects of learning as people engage with learning activities, one another, and their identities as learners and doers of particular activities.
3) Role of cultural practices for learning and the understanding that arrangements and values for learning are themselves cultural practices.

These three insights support the placement of learning in the center of Illeris' triangle where cognition is balanced by self and interaction of self with the activity and the social and cultural environments.

Sawyer (2005) further verifies the ideals present in Illeris' triangle. In his introductory chapter to the Cambridge Handbook of The Learning Sciences, justifying that learning science reform is based on professional practice, he states that "knowledge is not just a mental picture inside the learner's head; instead, knowing is a process that involves the person, the tools, other people in the environment, and the activities to which that knowledge is applied."

In summary, Illeris has developed a model for conceptualizing learning. We have described the model and provided evidence that the works of modern day leaders in learning science, Bransford and Sawyer, validate Illeris' model. Illeris identifies his model as being constructivist (2003). Following is an overview of constructivism.

2.3.2. CONSTRUCTIVISM

Rooted in the works of Jean Piaget and Lev Vygotsky from the early 1900's, the premise of constructivism is that rather than knowledge being acquired from others, each individual constructs much of what they learn (Schunk, 2009). Further, the learner's own experiences are integrated into what is learned (Jarvis, Holford, & Griffin, 2003). In contrast to instructionism, where the teacher is seen as the expert who delivers knowledge in one direction to the learner, in constructivism the teacher works from around the edges to empower the learner to build the knowledge for herself (Schunk, 2009).

There are three paradigms of constructivism: exogenous, endogenous, and dialectical. In exogenous constructivism, learning happens as the learner interprets his environment. Endogenous constructivism is a re-working of knowledge structures from within the learner's own mind. Dialectical constructivism is the construction of new mental frameworks that takes place at the intersection and interaction between the environment and the individual (Moshman, 1982).

Vygotsky (1978) presented a model for understanding the relationship between the learner and more capable guide to learning, whether teacher or peer. The distance between the level of the learner and the guide is termed the Zone of Proximal Development, and it is in this zone that cognitive change can happen. Tharp and Gallimore (1988) described stages in the ZPD to include being assisted by more capable others, constructing one's new knowledge, restructuring through internalization leading to automatization, and deautomatization, which can result in loss of the automated knowledge/skills through loss of practice or time since use, which would necessitate revisiting the ZPD.

Connections can be made to Illeris' four types of learning as stage 1 would be the beginning of cumulative learning. Assimilative learning takes place through stage 1 and into stage 2. Accumulative learning follows through stage 2 and into stage 3. The ZPD model doesn't explicitly address Illeris' transformative learning.

In The Process of Education, Bruner (1977) identified his constructivist-based principles of learning. The first principle addressed readiness of the learner to learn. The second principle brought forth the spiral model of learning that Sheppard et al. (2009) revisited in Educating Engineers. Here the fundamental principles are revisited at increasing levels until mastery is achieved. Bruner's third principle stated that the learner should have to actively fill in the gaps, that learning should go beyond the presented information, thus the learner must actively construct knowledge. Social constructivism goes beyond the individual constructing her own knowledge, to the public space where meanings are socially negotiated (Bruner, 1990). In other words, constructed knowledge is a part of, not distinct from, the social and cultural fabrics within which it is created.

To place these understandings of knowledge construction in Illeris' triangle, we have constructed content from the upper left vertice, readiness for learning from the upper right vertice, and interaction with peers, teachers, culture and society, from the lower vertice. We have placed constructivism/social constructivism in the middle of the triangle. Illeris places Bruner and Vygotsky works along the left leg of the triangle, between the stronger influences of content and interaction, with less from the incentive.

2.3.3. APA PRINCIPLES

Reflecting a social constructivist approach (Schunk, 2009), in 1997, the American Psychological Association (APA) developed learner-centered psychological principles to provide a forward-looking framework for education reform. These 14 principles are divided into four categories: cognitive/metacognitive, motivational/affective, development/social, and individual differences. The first 11 principles, when taken individually, can be placed on Illeris' tension triangle. They demonstrate importance at all three vertices and in the center. Figure 2.11 shows the APA principles.

Cognitive and Metacognitive Factors

1. Nature of the learning process – The learning of complex subject matter is most effective when it is an intentional process of constructing meaning from information and experience.
2. Goals of the learning process – The successful learner, over time and with support and instructional guidance, can create meaningful, coherent representations of knowledge.
3. Construction of knowledge – The successful learner can link new information with existing knowledge in meaningful ways.
4. Strategic thinking – The successful learner can create and use a repertoire of thinking and reasoning strategies to achieve complex learning goals.
5. Thinking about thinking – Higher order strategies for selecting and monitoring mental operations facilitate creative and critical thinking.
6. Context of learning – Learning is influenced by environmental factors, including culture, technology, and instructional practices.

Motivational and Affective Factors

7. Motivational and emotional influences on learning – What and how much is learned is influenced by the motivation. Motivation to learn, in turn, is influenced by the individual's emotional states, beliefs, interests and goals, and habits of thinking.
8. Intrinsic motivation to learn – The learner's creativity, higher-order thinking, and natural curiosity all contribute to motivation to learn.

Intrinsic motivation is stimulated by tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control.

9. Effects of motivation on effort – Acquisition of complex knowledge and skills requires extended learner effort and guided practice. Without learners' motivation to learn, the willingness to exert this effort is unlikely without coercion.

Developmental and Social Factors

10. Developmental influences on learning – As individuals develop, there are different opportunities and constraints for learning. Learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account.
11. Social influences on learning – Learning is influenced by social interactions, interpersonal relations, and communication with others.

Individual Differences Factors

12. Individual differences in learning – Learners have different strategies, approaches, and capabilities for learning that are a function of prior experience and heredity.
13. Learning and diversity – Learning is most effective when differences in learners' linguistic, cultural, and social backgrounds are taken into account.
14. Standards and assessment – Setting appropriately high and challenging standards and assessing the learner as well as the learning progress -- including diagnostic, process, and outcome assessment -- are integral parts of the learning process.

Figure 2.11. American Psychological Association learner-centered psychological principles (APA 1997)

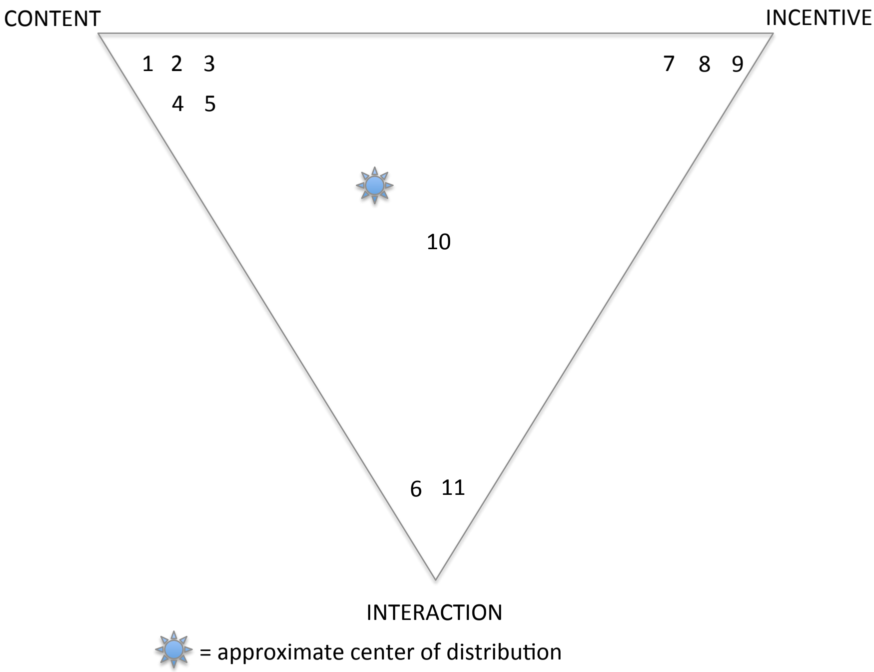


Figure 2.12. Distribution of APA principles on Illeris triangle

The APA took a stand saying the evidence (at the time) on learning pointed toward models that follow these principles. The principles are, for the most part, social constructivist in nature. Viewing these principles through the lens of Illeris' tension triangle shows the principles being valued in all three dimensions. Figure 2.12 shows the APA principles super-imposed on Illeris' triangle. A geographical center of the principle would be shaded to the upper left of the triangle's centroid. From our perspective, nearly 20 years after the APA principles were published, there is imbalance in this distribution. It appears as though the APA principles, at least in quantity, did not give appropriate value to the social and environmental impacts on learning.

This criticism aside, we see value in using the APA principles, taken individually, as a way to view the learning attributes of the elements in a learning environment. In future sections and chapters, the Illeris triangle and the APA principles are used to ground aspects of learning in general and the IRE model in specific.

2.3.4. ELEMENTS OF LEARNING AND LEARNING ENVIRONMENTS

We now present literature-based descriptions of the following relevant additional components for designing of learning and learning environments: development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity. We will describe each, discuss their relevance, and position them in the models of Illeris and their connection to the APA principle

Kafai (2006) distinguishes between constructivism, which is a theory of knowledge development, and constructionism, which is a theory of teaching and learning that is based on constructivism. As this learning theory section of Chapter 2 develops, we move from a view of what learning is, toward the frontiers of how learning happens. As the world evolves technologically and becomes more complex, instructionism continues to fail to meet the educational needs of learners (Sawyer, 2005). In the past 20 years, emerging from the theory of constructivism, social constructivism, and the concept of constructionism is a new science of learning.

Bransford et al. (2000) imply that learning should consist of deeper conceptual understanding, focus on the learner in addition to the teacher, use prior knowledge to build new, focus on the learning environment, and focus on reflection. Their work is closely paralleled by the afore-mentioned principles published by APA. The concepts that make up this new science of learning are the foundations for the development of learning systems: development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity.

These elements range from attributes specifically focused on the learner to attributes of the structures around the learner. Following are the theoretical underpinnings of these concepts, followed by a placement of the components in Illeris' model of learning.

Developing Expertise

Experts are differentiated from novices in that they have the ability to efficiently encode domain specific details to quickly process and adapt to unique situations. They have substantially large sets of complex long-term memory structures and procedures (Sawyer, 2005; Schunk, 2009). In addition to having more knowledge, experts have that knowledge identified in a manner called conditionalizing, so that they may identify its relevance or irrelevance to any particular situation. Experts tend to organize their knowledge around the fundamental principles of the domain while novices tend to rely on memorizing procedures (Bransford et al., 2000). As a result of these abilities of experts, they can recognize features in problems that novices do not notice. Another attribute distinguishing experts from novices is their proficiency at reflecting on their thinking during the thinking processes (Sawyer, 2005).

Bransford et al. (2006) developed a model for adaptive expertise that differentiates between routine experts and adaptive experts. The difference is in the ability to innovate. They put forth that most educational environments are designed for routine expertise and purport that learning environments, to develop adaptive expertise should heavily emphasize reflection and metacognition, involve inquiry focused on confirming/disconfirming theories rather than following standard procedures, and involve students in inventing and developing instruments to work more efficiently.

A connection of developing expertise to the Illeris model of learning would place it in the upper left section of content as this work on expertise is focused on cognition with little connection to incentive or interaction.

Reflection

As indicated in Section 2.2, reflection is highly valued in the design and implementation of the IRE model. We considered it an essential element in the curriculum and here, again, as an element in the design of a learning environment. In his landmark texts, The Reflective Practitioner and Educating the Reflective Practitioner, Donald Schön presents the perspective that:

> *"In the varied topography of professional practice, there is a high, hard ground overlooking a swamp. On the high ground, manageable problems lend themselves to a solution through application of research-based theory and technique. In the swampy lowland, messy confusing problems defy technical solution. The irony of this situation is that the problems of high ground tend to be relatively unimportant to individuals or society at large, however great their technical interest may be, while in the swamp lie the problems of greatest human concern. The practitioner must choose. Shall he remain on the high ground where he can solve relatively unimportant problems according to prevailing standards of rigor, or shall he descend to the swamp of important problems and nonrigorous inquiry" (Schön, 1987).*

Schön goes on to argue that the ability to reflect-in-practice is a form of artistry necessary for success in the swampy world of real, complex, ill-structured problems. Cowan (2006), developing his model for reflection, presented two principles: "people who think about how they *do it*, will improve at *doing it*" and "people who think about how well they *do* things and how well they *could do* things are more effective self-directed learners."

Reflecting on one's own thinking and learning is part of the metacognitive process (Sawyer, 2005) and, as alluded to above, is an essential component in the development of expertise and in the actions of professional practice. Thus, it is essential that developing, through explicit practice with feedback, the ability to reflect is a part of learning environments (Bransford et al., 2000). Further, reflection becomes essential as the engineering student begins to understand why design decisions are made and he connects them to the responsibilities of the engineer to society (Dreher, 2015). To connect reflection with Illeris' model of learning, we look to one of his four types of learning. Accommodative learning takes place when learners, in a new environment, reflect on previously established mental schemes to activate a restructuring, resulting in new, more developed mental schemes.

Metacognition

Early work on metacognition was done by Flavell (1979) who defined it as "knowledge and cognition about cognitive phenomena." This is often translated as thinking about thinking. To operationalize metacognition for use in developing learning environments, it can be considered as having two dimensions: declarative and procedural. Declarative metacognition is a person's understanding of a learning task, its requirements, and strategies for accomplishing the task. Procedural metacognition is the person's ability to carry out the strategies. This includes task identification, monitoring the progress of the task, evaluating that progress, and making changes in the procedure as a result of the evaluation (Flavell, 1979). For an engineer to solve the complex and ill-structured problems in Schön's "swamp," performing these metacognitive tasks, accomplished through reflective activities, is essential. It could be argued that these are the same skills and abilities necessary to achieve the innovation levels necessary for adaptive expertise. The importance of metacognition is confirmed in APA principle 5 (Figure 2.11), thinking about thinking – higher order strategies for selecting and monitoring mental operations facilitate creative and critical thinking. Bransford et al. (2000) declare, and provide evidence in support, that metacognition increases the degree to which students can transfer previous learning to new situations. In regards to Illeris' models, metacognition is placed in the content corner and is essential to accommodative learning.

Scaffolding

The idea behind scaffolding in a learning environment is that the learner is treated as an apprentice learning a trade, where the trade is cognition rather than a physical process. The physical apprentice observed the master, then slowly learned the trade under the master's scaffolded guidance. As experience led to skill, the master's scaffolding was slowly removed until no further guidance was required, and the apprentice became the master. Cognitive apprenticeship is a model for learning environments in which teachers are the master and the students are learning through "on-the-job training." Here, teachers "identify the processes of the task and make them visible to students; situate abstract tasks in authentic contexts, so that students understand the relevance of the work; and vary the diversity of situations and articulate the common aspects so that students can transfer what they learn" (Collins, Brown, & Holum, 1991). From a constructivist point of view, scaffolding can be used to promote learners' active participation in the development of their learning goals and provides the learners guidance under which they can construct their new knowledge (Sawyer, 2005). In this type of learning environment, the teachers don't deliver new knowledge, but rather guide and prompt, through questioning, the learner development of the knowledge. In describing environments in which adaptive expertise can be developed, Bransford, et al. (2006) list attributes of scaffolding through cognitive apprenticeship. APA principle #2 addresses the requirement of guidance and inquiry in the development of increasing levels knowledge. Scaffolding, when placed in the Illeris model, would lie on the leg between content and interaction as it is necessary for there to be a social interaction with the guide during the development of knowledge.

Motivation

Motivation is connected to the individual, her experiences and her goals, as well as to context, placing it in the setting of time, place and people (Rogers, 2002). Vanasupa, Stolk, and Herter (2009) argue that since "acquiring new knowledge and skills is recognized as a process of change, largely controlled and internally constructed by the learner," the learner's motivation is central to the initiation, continuation, and magnitude of the learning. There is much to support this in the literature (e.g. Blumenfeld, Kempler, & Krajcik, 2006; Bransford, Vye, & Bateman, 2002; Rogat, Linnenbrink-Garcia, & DiDonato, 2013). Further, the intensity of the learner's motivation is due to an interrelationship between interest, value, and autonomy, and these three components have cumulative interdependence. The more value the learner assigns to a task, the more interested he becomes. The more autonomy in the learning process, the more interest and value (Vanasupa et al., 2009). The choices to engage in and monitor learning are components of self-regulated learning (Boekaerts, Pintrich, & Zeidner, 2005). Thus, higher degrees of motivation lead to higher degrees of self-regulation, and both lead to higher degrees of engagement in active learning. Finally, higher degrees in engagement in active learning lead to higher degrees of mastery of core engineering competencies (Prince & Felder, 2006).

Motivation's importance in the construction of learning and its dependence on social interaction make it a substantial component in the design of the learning environment. APA principles 7,8, and 9 account for the importance of motivation in the likelihood of the learner exerting effort for mastery. Motivation would certainly be in the incentive corner of Illeris' triangle, though, as shown above, motivation is impacted by social interaction and directly impacts cognition.

Situativity

A situative view places knowledge "as distributed among people and their environments, including objects, artifacts, tools, books, and the communities of which they are a part" (Greeno, Collins, & Resnick, 1996). Lave and Wenger presented the social character of learning, presenting it as more than the reception of factual knowledge or information. "Learning is situated in the pathways of participation in which it takes places... situated in the learning activities, communities, cultures and societies in which it takes place" (Lave & Wenger, 1991). Johri and Olds (2011) summarize situated learning. Here, knowing is distributed in the learner's social and cultural world. Learning takes place through engaged participation, social practices of inquiry, practices of formulating and solving realistic problems. Learning environments support the development of positive identity. Students participate in assessment. Further, Johri and Olds connect situativity with the learning of engineering broken down into the use of representations, alignment with professional practice, and emphasis on design. Engineering cognition is based on representations that take on various forms such as words, visuals, and tools. Professional practice includes an identity alignment with the people and cultures of the working communities. Design is activity rooted in collaboration, artifacts, tools, and the contexts in which the design will be employed. This clearly places engineering learning as being "distributed among people and their environments, including objects, artifacts, tools, books, and the communities of which they are a part." In his story Jakob and Manipulator, Henriksen explores the complex interactions between the designer, the environment, and the technology, demonstrating the importance of situativity (Henriksen, 2012). Relating situativity to previously discussed elements, clear connections can be made to motivation and reflection. It is at the core of social/cultural constructivism. APA principle 11 highlights the influence of social interaction on learning. In Illeris' model, situativity is at the bottom vertex of interaction.

Learning Community

Closely related to situativity is the concept of the learning community. Lave and Wenger (1991) pioneered the concept of *communities of practice.* They defined community as that place in which "participants share understandings concerning what they are doing and what that means in their lives and for their communities." They describe participants as "members who have different interests, make diverse contributions to activity, and hold varied viewpoints." A community of practice, then, is the relationships between the people, their activities, and their world through time and with respect to other communities. Participation in learning communities has recently, through research, been linked to increased positive engagement (Zhao & Kuh, 2004). Through engagement, the learning environment element of learning community connects to motivation. This places learning communities on the leg of Illeris' triangle between emotion and interaction. It connects directly and indirectly with APA principles 6, 7, 8, 9, and 11. The social aspect of constructivism implies a community of learners. In conclusion, learning communities are embedded in the fabric of constructivist learning and cannot really be considered as separate; however, in the design of learning environments, special attention can be given to the establishment of community.

Identity

Just as with reflection, identity's value has us considering it in both Sections 2.2 and 2.3. Throughout an engineer's education, he builds a concept of himself in relation to the activities and values of his profession. The strength of that concept is considered his professional identity, his personal identification with his career choice. This is a person's perception through the lens of himself and from the continuous feedback from his environment. In engineering education, professional identity has been studied and found to have a positive correlation with student learning (Eliot & Turns, 2011; Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008). Further, Plemmons (2006) makes a case for identity and learning:

> *"When students grow more mature, they become more responsible for their decisions and actions. This results in them becoming more self-directed in their learning and less dependent on their teachers."*

Many educational activities are identified as building positive external (expectations of others about the professional responsibilities) and internal (person's own values as they relate to the profession) identity. Examples include internships (Dehing et al., 2013), service learning (Dukhan, Schumack, & Daniels, 2008), participating in learning communities (Du, 2006) and PBL (Du, 2006).

There is certainly inter-relativity in the previously discussed elements of learning elements of situativity, motivation, learning communities. Situativity and learning community participation have been shown to build identity, and higher identity improves motivation (Lave & Wenger, 1991). Identity through social interaction fits on the right leg of Illeris' triangle, on the line between emotion and environment. APA principles 7-11 involve these interactions between motivation and social learning environment that both impact and are impacted by identity. Dehing (2013) makes the arguments that, because of the importance of identity building, learning environments explicitly develop engineering identity from the very beginning of education, treating students as student engineers as early as possible.

2.3.5. FRAMEWORK FOR CLASSIFYING

We have identified essential components of the learning environment and used the literature to validate their importance. These essential elements are inter-related, and a concept map showing this has been created. Illeris' model has been presented, validated, and given value to. The tensions in Illeris' triangle have been used to place constructivist principles and essential elements in learning environments. In Figure 2.13, we superimpose Illeris' triangle onto the concept map of learning environment elements to illustrate their respective positions. The Illeris model, principles of constructivism, and elements of learning described above provide the aspects against which models of learning can be evaluated.

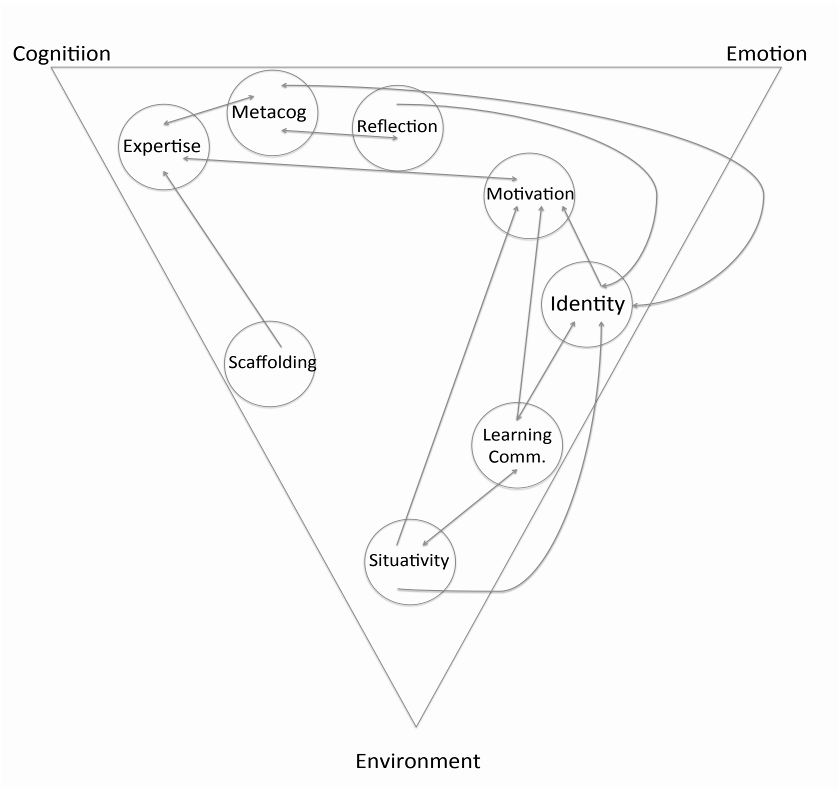


Figure 2.13. Illeris' triangle superimposed onto concept map of learning elements

The purpose of this section has been to provide a theoretical basis to address the objective of analyzing the IRE model through theory. In subsequent sections and chapters, PBL and the Iron Range Engineering model of PBL will be described and analyzed in terms of Illeris' triangle, the APA principles, and the elements of learning and learning environments.

2.4. PBL

With the ultimate goal of this volume being a description and subsequent analysis of the Iron Range Engineering model of PBL, the goal of this section is to provide PBL theoretical background for *detailing how the IRE program implements the principles of PBL.* The previous two sections took broader looks at curricular and learning theory. The next step is to focus specifically on PBL. We will do this by defining PBL in the literature and placing it in learning theory. Further, we will consider the benefits and critiques of PBL, especially in meeting the calls for change. The final goal of this section, as it was in the previous sections, is to establish a framework for analyzing the IRE PBL model in a future chapter. A summary of the Aalborg PBL model will be provided as a base model for the development of the IRE model.

2.4.1. DEFINING PBL

Problem-based learning (PBL) has its origins as a core curriculum at McMaster University medical school in the 1970s (Neufeld & Barrows, 1974) and the adaptation of that model at other medical education facilities around the world (Wood, 1994). It's adoption and adaptation continued as Roskilde University and Aalborg University in Denmark, Maastricht University in the Netherlands, and Linköping University in Sweden were founded and established on problem-based learning in the 1970's (Kolmos, Fink, & Krogh, 2004).

Even though problem-based learning models are different as it is practiced around the world, Barrows (1996) identified six core characteristics for all problem-based learning:

- Problems form focus and stimulus for learning
- Problems are the vehicle for development of problem-solving skills
- New information is acquired through self-directed learning
- Student-centered
- Small student groups
- Teachers are facilitators/guides

In engineering education today, PBL is also used to refer to project-based learning. This creates some confusion as to what defines a PBL curriculum. Of particular interest in this study is the Danish approach to PBL, it is considered an approach to PBL that is a "combination of a problem-based and a project-organized approach" (Kolmos et al., 2004). At Aalborg, the traditional model of PBL is based upon problem-based project work.

Prince and Felder (2006) in their study of inductive learning methods sought to clarify a definition for problem-based and project-based learning. They defined problem-based learning as when "students are confronted with an open-ended, ill-structured, authentic (real-world) problem and work in teams to identify learning needs and develop a viable solution." They emphasized the role of the instructor as the facilitator in this process, as compared to one of "information source," which they play in a traditional education model. Further, they defined project-based learning as beginning with "an assignment to carry out one or more tasks that lead to the production of a final product – a design, a model, a device or a computer simulation. The culmination of this project is normally a written or oral report summarizing the procedure used to produce the product, and presenting the outcome" (Prince & Felder, 2006).

Based on these definitions, the problem-based learning method is more open-ended than the project-based learning method. Similarly, Savin-Baden (2003, 2007) does a compare and contrast of the two PBL approaches, primarily on the premise that problem-based learning is more process-focused, and that project-based learning is more about the product and is narrower in scope.

These discussion and definitions are primarily about the scope of the problem and projects involved. More important to PBL, for this study, than the scope of the project or problem work is the learning experience they can provide for students. "The outcomes of the PBL learning experience are designed to help students:

1) construct an extensive and flexible knowledge base;
2) develop effective problem(project)-solving skills;
3) develop self-directed, lifelong learning skills;
4) become effective collaborators; and
5) become intrinsically motivated to learn" (Barrows & Kelson, 1995).

These potential outcomes make PBL a curricular approach of interest for meeting the calls for change in engineering education. This will be discussed later in this section.

Kolmos (1996) states that "the main idea beyond both project work and problem-based learning is to emphasize learning instead of teaching." Kolmos et al. (2014) argue that "project-based learning cannot exist without a problem-orientated approach." They use two definitions to support this understanding of project-based learning. First, the Capraro and Slough (2009) definition, "a well-defined outcome and an ill-defined task. PBL for the purposes here is the use of a project that often results in the emergence of various learning outcomes in addition to the ones anticipated." The other is the Algreen-Ussing and Fruensgaard (2002) definition of a project as "a complex, unique, and situated task that cannot be repeated and will always involve an open approach."

The definition of project-based learning we will use, in this study, is that every project starts with a problem (Kolmos, de Graaff, & Du, 2009). The problem may be a curiosity; a contradiction to be resolved; an interest to make something better; a need of a customer to be accomplished; or an industry need to be met. The learning process starts with the problem. The project adds authentic complexity to the problem solving and involves real-world complex solving strategies to solve the problem at the heart of the project. The project adds to the learning process the need to report and have a timeline that reflects the work world students will enter.

This definition will be used in defining project-based learning (PBL) in the remainder of this chapter and thesis. Given their similarity, external discussions and references included in the discussion will include both problem- and project-based learning.

De Graaff and Kolmos (2003, 2007) identified a set of common learning principles based on an analysis of PBL models and the "learning theories that form the basis of both PBL models such as Dewey, Kolb, and Schön" (Kolmos, de Graaff, & Du, 2009). These principles help draft a definition of PBL that is beyond the curricular level and are at a more philosophical and abstract level. They form a set of principles that can cross specific contextual conditions. The identified three approaches to the learning principles are the Learning Approach, the Contents Approach, and the Social Approach, as shown in Figure 2.14. These learning principles will be discussed further within the learning theory discussion of PBL.

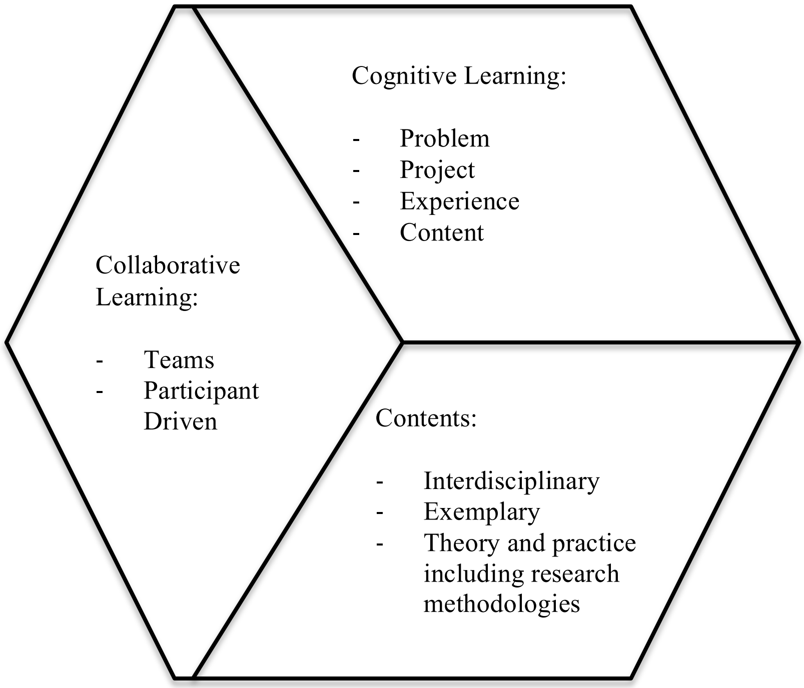


Figure 2.14. PBL learning principles (Kolmos, de Graaff, & Du, 2009)

2.4.2. AALBORG PBL MODEL

Before continuing the discussion of learning principles and learning theory related to PBL, the discussion of PBL will continue with a closer look at the Aalborg PBL model. It served as a basis in the development of Iron Range Engineering.

As mentioned earlier, it is a project-organized; problem-based learning approach to student learning. In 2004, Aalborg University published a book on the Aalborg PBL model. It was the results of an internal conference on the model (Kolmos et al., 2004). In it is a description of the traditional Aalborg PBL model with the following characteristics:

- Founded on problem-based project work – half of the student time is spent on project work and the other spent on lecture/course work.
- Project work is done in teams – in the students' first year, the teams start with 6-7 students and reduce to 2-3 students in the final semester of the students' educational experience.
- Same model for each semester (ten semesters total)

- o Project work supports framework of prescribed learning theme for the semester.
- o 80% of student time is spent on project and related courses. The remainder is spend on fundamental or compulsory courses.
- o Students formulate project proposals.
- o Supervisor approves proposal, responds project progress, and participates in group examination at semester end.
- o Majority of courses must relate to semester theme.
- o Students are to apply coursework to project.
- o Course summative assessment is a group examination.

The curriculum is structured to be fundamentally progressive each semester. As the learning progresses from semester to semester, more flexibility is allowed to the student groups. Projects come from outside entities, such as industry and government or from the personal interests of either the students themselves or faculty. The main focus of the Aalborg model is that the project is at the center of all student learning.

The Kolmos et al. (2004) edited book concludes with a chapter from Joachim Höhle that is written from the perspective of evaluating it from outside the Danish culture. Of specific interest is the discussion on adaptability of the model outside Denmark. He identifies the need for a short power distance between faculty and the students and flexibility in student evaluation for the model to be successfully utilized. Cultural factors will affect how the model is adapted as it is adopted. The cultural and social factors will be visited in the next section as PBL is positioned in the Illeris model and social constructivism.

2.4.3. PBL IN LEARNING THEORY

Next, PBL is positioned within the theoretical underpinning of the Illeris model, social constructivism, and elements of learning from Section 2.3. (Wilkerson & Gijselaers, 1996) proposed three principles of learning to connect PBL with education learning theory:

1) Learning is a constructive and not a receptive process.
2) Metacognition affects learning.
3) Social and contextual factors influence learning.

2.4.3.1 Illeris model

As described previously, the (Illeris, 2007) model identifies three dimensions of learning: content, incentive, and interaction. (Kolmos & Graaff, 2014), in their analysis of PBL models and practices, identify three main learning principles: learning approach, social approach, and contents approaches.

Illeris's content dimension focuses on the knowledge and skills that are an intended outcome of a learning approach; this is the "what" of student learning. Connecting the content dimension to PBL, (Kolmos & Graaff, 2014) identify the c*ontents approach* as the identification of the knowledge and skill as the intended outcomes of a PBL curriculum. An exemplary practice for the *contents approach* is students having the "freedom to choose projects within a given theme" (Kolmos & Graaff, 2014).

Second, is the incentive dimension of the Illeris model where the motivations for learning are considered; this is the "why" of student learning. It connects to PBL through the *learning approach* with the utilization of real life projects in which students must identify, analyze, create, and report results. The project or problem "forms a starting point for the learning process, as the problem indicates the purpose of the learning process. This means that students can orient their reading toward this particular problem to gain a deeper understanding" (Kolmos & Graaff, 2014). Critical to the learning approach is the self-directed learning that takes place in the collaborative setting of the team as they negotiate the learning process.

Third, is the interaction dimension of the Illeris model, which considers the interactions that take place during the learning process; this is the "where" and "how" of student learning. It is the social aspect of learning. It connects to PBL through its *social approach* with the team-based learning and the "interaction between the individual and the group" (Kolmos & Graaff, 2014).

2.4.3.2 Social constructivism

Work in social constructivism suggests that learning occurs with individuals in a social context (Vygotsky, 1978). Project-based learning with individuals in teams working on projects is, by its very nature, social as students seek to create solutions to these projects. An underlying premise is that individuals construct much of what they learn in solving these projects (Schunk, 2009); as knowledge that didn't exist for them before must be constructed while they seek solutions to the projects.

If we look at Jonassen's (1991) five tenets for describing constructivism and connect them with the PBL learning approaches identified by de Graaff and Kolmos (2003, 2007) as shown in Table 2.2, we can see that PBL is fundamentally based upon constructivism assumptions (Marra, Jonassen, Palmer, & Luft, 2014).

Table 2.2. Constructivism tenets and PBL learning principles

Five Tenants for Describing Constructivism - Jonassen	PBL Learning Principles – de Graaff and Kolmos
1. Knowledge is constructed via interactions with the environment 2. Reality (the sense we make of the world) is in the mind of the knower 3. Meaning and thinking are distributed among the culture and community in which we exist and the tools we use 4. Knowledge is anchored in and indexed by relevant contexts Knowledge construction is stimulated by a question or need or desire to know	**Cognitive Learning Approach** - Problem - Experience - Project - Context **Contents Approach** - Interdisciplinary - Exemplary - Theory and practice including research methodologies **Social Approach** - Teams - Participant-driven

<u>Knowledge is constructed via interactions with the environment.</u>

Jonassen (1991) describes humans as learners that perceive and interpret as they construct an interpretation of the world around them. Through this cognitive and interpretive process, they construct new mental models as they try to make sense of accommodating existing beliefs and knowledge representations with the new ideas, phenomena, and ways of understanding.

If we look at PBL, the utilization of projects creates an authentic environment or context where students need to construct new knowledge. As part of the *cognitive learning approach,* the problem to be solved serves as “the starting point for the learning process.” The project aspect adds more complex strategies that will challenge students to acquire new knowledge and understanding to solve these more complex challenges. The project aspects of doing a real world project, working with a team, developing a final report, and having a deadline to meet all add to the authenticity that makes PBL an effective learning approach.

<u>Reality (the sense we make of the world) is in the mind of the knower.</u>

Jonassen (1991) states the sense-making process is something that is unique to each learner. Contrary to the linear, consistent approach of traditional educational processes, each learner has a perception of the external world around her and therefore has a set of learning experiences that is unique to them as an individual.

This does not mean that the process cannot be communicated and expressed to others, but it does mean that the process cannot be readily transmitted or acquired by others in a duplicate fashion.

If we look at PBL, this is reflected in both the *cognitive learning* and *contents approaches*. Since the problem serves as the starting point for learning, it allows each learner to start with their current understanding of the external world, specifically in the context of the particular problem to be solved. As solutions are sought to the problem, as part of the project work, the individual must evaluate their own current models and determine if they are adequate for use with the particular problem. If they are not, then the individual must go through a unique set of learning experiences to add to, or adapt, these models to a level adequate for the particular problem.

Given the interdisciplinary nature of the *contents* of a problem, the learning will span across the "traditional subject-related boundaries and methods" (Kolmos, de Graaff, & Du, 2009). This *contents approach* to PBL allows the individual knower to access all models and work across the discipline boundaries as he seeks a method to solve the problem.

Meaning and thinking are distributed among the culture and community in which we exist and the tools we use.

Jonassen (1991) proposes that as an individual engages in a learning community, the beliefs and values of that community influence the individual's own knowledge and beliefs. Cunningham and Duffy (1996) define this learning as changes in how an individual understands the external world as it relates to, or in relation to, the culture to which the individual is connected.

If we look at PBL, this plays out particularly well with the *social approach* of the team-based learning within the problem solving for the project. It is best summarized by:

> *"The team-learning aspect underpins the learning process as a social act where learning takes place through dialogue and communication. Furthermore, the students are not only learning from each other, but they also learn to share knowledge and organize for themselves the process of collaborative learning. The social approach also covers the concept of participant-directed learning, which indicates a collective ownership of the learning process and, especially, the formulation of the problem"* (Kolmos, de Graaff, & Du, 2009)

It is through this social process of collaborative learning that the individuals learn and grow in their understanding of the external world. At the same time, their knowledge and beliefs are distributed to their teammates as fellow participants in the learning community (Salomon, 1993).

Knowledge is anchored in and indexed by relevant contexts.

Jonassen (1991) explains that in the constructivism viewpoint, our ideas and skills consist, at least partly, in the situation or context where they were acquired or applied. In contrast, the ideas, concepts, rules, and laws that are learned in the abstract, separate from any context, have no real value or meaning. This approach can be at least partially attributed to traditional methods of instruction within engineering, where students "learn" a new concept through a lecture in which a professor goes through a mathematical derivation to derive the equation. Although one could argue that the mathematical proof provides context, the abstractness of this context is beyond where most undergraduate students are in their learning abilities. The mere teaching of facts and concepts, without context, prevents meaningful indexing of them by the individuals learning them. Without context, there is no indexing of learning to the features of a current or future application, where it may be relevant (Schank, Fano, Bell, & Jona, 1994).

If we look at PBL, the entire *cognitive learning approach* is based on the premise that learning takes place in the context of solving a problem as part of the project. Not only is there the immediate context of the problem to index the learning, but the recognition of the problem within the overall project and the determination of relevant solutions and pertinent information provides a much deeper level of anchoring and indexing for the individuals involved in the process.

Knowledge construction is stimulated by a question or need or desire to know.

Jonassen (1991) explains that, within the constructivist understanding of construction of knowledge, the acquisition of knowledge occurs through the dissonance between what an individual "knows" internally and what he is observing in the external world around him. Although things shared by others can be memorized, the dissonance truly comes when the learner is actively involved with making meaning of the difference between what is currently "known" by the individual and what the individual needs to or wants to know.

If we look at PBL, this is reflected in both the *collaborative learning* and *contents approaches*. The learning is participant-driven as they seek solutions to the problem they are trying to solve. The learning occurs when they recognize what is "known" is not adequate to solve the problem. This recognition creates the need or desire to know or understand the knowledge required to solve the problem and develop a solution for the project. The *contents approach* of PBL emphasizes the relationship between theory and practice in the problem approach. As the learner uses the analytical approach to solving the problem, a theory must be utilized as the heart of the approach. Each problem causes the learner to grow in his understanding of the theory through the necessary process of relating or adapting it to each unique application. Kolmos, de Graaff, & Du (2009) point out that this facilitates the individual's training in research methodologies.

2.4.3.3 APA principles

The APA principles for effective learning are, for the most part, social constructivist in nature. Connecting these principles to PBL, they are used to ground aspects of the PBL learning. The first five *cognitive and metacognitive factors*: 1) nature of the learning process, 2) goals of the learning process, 3) construction of knowledge, 4) strategic thinking, and 5) thinking about thinking ground the learning occurring in the context of the project. The complexity of the projects creates an intentional learning process that requires students use higher order strategic thinking strategies to identify learning goals for developing new knowledge to complete the project and then link this with previous knowledge with new knowledge.

The *motivational and affective factors*: 7) motivational and emotional influences on learning, 8) intrinsic motivation to learn, and 9) effects of motivation to learn, are connected to the genuine experience created by the project. Students enter engineering to become engineers, the curiosity, and motivation that led students to make the decision to enter the study of engineering is positively affected by the novelty and difficulty of the projects when students have a choice in selecting the project and control over the learning process within the project. This in turn has a positive effect on creating a strong, natural intrinsic motivation for what and how much is learned.

In regards to the remaining principles, the social interactions, interpersonal relations, and communication within the team environment directly relate the PBL curriculum to the APA principles 6) context of learning and 11) social influences on learning. As discussed earlier relating to the Illeris dimensions of learning, PBL learning is within and across the physical, intellectual, emotional, and social domains of APA principle 10) developmental influences on learning. The *individual differences factors* are not necessarily connect to the PBL curriculum, but each individual student experience is still grounded in them as they traverse the curriculum.

2.4.3.4 Elements of learning and learning environments

These elements, development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity, were then constructed into a concept map that was superimposed on the Illeris triangle. We will make an initial underpinning of these elements to PBL; in a later section we will specifically connect them to the development of the new PBL model.

Development of Expertise

Experts, as compared to novices, tend to organize their knowledge around the fundamental principles of their domain of knowledge. PBL supports this element in that the approach to solving the problem in the project requires the learners to first determine the fundamental principle of importance to solve the problem. The interdisciplinary nature of the PBL work does not make the selection of the fundamental principle an arbitrary one. This facilitates the life-long process of the student developing expertise, and the approaches that an expert takes in problem-solving.

In contrast, traditional educational approaches, at least within engineering education, make the identification of "which fundamental principle to use" very much an arbitrary decision. In fact, most times, there isn't necessarily even a recognizing of the fundamental principle, but more an organizing of knowledge around "what solution do I use with this type of problem?" This hardly creates an environment to foster the development of expertise.

Reflection

Schön's argument for the ability to reflect-in-practice as an art form for success in the swampy world of real, complex, ill-structured problems is an integrated part of the problem-solving process of PBL. As learners work on the problem and interact with their teammates, they constantly have to reflect on their current internal understanding as it compares to the understanding communicated by others and the reality of the external, real-world system with which they are dealing. Through this critical part of the PBL process, students practice and develop the ability to reflect-in-practice for future professional practice.

Metacognition

Metacognition, often translated as "thinking about thinking," has two dimensions: the declarative dimension and the procedural dimension. Declarative metacognition, an individual's understanding of a learning task, is an integral component of PBL problem solving. Given the ill-structured nature of the problem to be solved within the project, the students must continually reflect on their individual and overall team understating of the problem and the strategies being used to solve the problem, and also whether the understanding and strategies are still currently correct.

Procedural metacognition, a person's ability to carry out strategies, is also an integral component of PBL problem solving. As each problem, to be solved within a project, is unique in how it will be solved, each learner will need to identify tasks specific to the project, monitor the progress of the task, evaluate that progress, and make changes in the procedure as a result of the evaluation. If the learner identifies a task that she does not know how to accomplish, she has created an authentic learning opportunity to gain the knowledge necessary to complete the given task.

Scaffolding

From a constructivist point of view, scaffolding can be used in PBL curriculum to promote learners' active participation in the development of their learning goals and provide guidance under which they can construct their new knowledge. Within the project work, instructors don't deliver new knowledge, but rather guide and prompt, through questioning, the learner development of the knowledge to solve the problems. Given the uniqueness of the learning process for each individual and the uniqueness of each problem, the instructor must provide the correct amount of guidance and prompting to allow the learning and work to move forward, but must, at the same time, allow for it to be a student-driven process. The amount of scaffolding will reduce as the learners are better able to access their own learning and increase their ability to learn new knowledge.

Motivation

As identified previously, the learner's motivation is connected to the individual, his experiences and goals, as well as to the learning context, the setting, time, place, and people. The *collaborative learning approach* of PBL creates the context that learning is carried out on a project that the student was part of selecting, along with a team that he was part of creating. The participant directed nature of the work creates the ideal context for student motivation due to the interest, value, and autonomy the student has in the process. The more value the learner assigns to the task; the more interested the student becomes. The more autonomy in the learning process, the more interest and value.

Situativity

Situativity is at the bottom vertex of interaction in the Illeris triangle model. The environment in which the learning takes place supports the student development of identity. The authentic nature of the problem solving within the project work creates a learning environment that closely reflects the professional environment in which students will find themselves.

Learning Community

The concept of learning community is closely related to situativity. The social aspect of constructivism implies a community of learners. A PBL program provides a larger community of multiple students who are all engaged in the process of becoming something, in this case, engineers. This larger community is embedded in the fabric of constructivist learning. It provides a social aspect for all learners going through a growth process at similar stages of their learning. The teams themselves provide an additional and closer knit learning community for the learner. Even though each learner experiences an individual learning process, the learning experiences of the project team-mates will closely align with each of the individuals on the team. The multiple learning communities provided by project-based learning creates motivation for each learner, as well as a positive engagement by each learner.

Identity

As identified earlier, there is a positive correlation between student learning and the development of the learner's professional identity as she builds a concept of herself in relation to the activities and values of her profession within her engineering education experience.

As we have positioned project-based learning within learning theory using the Illeris model, social constructivism, and elements of learning from Section 2.4, we now turn the discussion to critiques and evaluations of PBL.

2.4.4. PROJECT-BASED LEARNING BENEFITS AND CRITIQUES EVALUATIONS

Both the 2010 and 2013 UNESCO reports on engineering identify the potential of PBL for meeting the needs of the profession and the society today and into the future. Several other prevalent publications identify the use of PBL as a critical component of transforming engineering education (Du, 2006; Felder & Brent, 2003; T. Litzinger, Lattuca, Hadgraft, & Newstetter, 2011; Sheppard et al., 2009).

The 2010 UNESCO Engineering: Issues Challenges and Opportunities for Development report on engineering development identifies a comprehensive list of the several benefits, from the literature, of PBL for students learning and also for the institution as a whole. The positive effects of the PBL model for identified student learning are:

- "Promoting deep approaches of learning instead of surface approach
- Improving active learning
- Developing criticality of learners

- Improving self-directed learning capability
- Increasing the consideration of interdisciplinary knowledge and skills
- Developing management, collaboration and communication skills
- Developing professional identity and responsibility development
- Improving the meaningfulness of learning"

The positive effects identified for the institutions with a shift to a PBL model:

- "Decreasing drop-out rates and increasing rate of on-time completion of study.
- Supporting development of new competencies for both teaching staff and students.
- Promoting a motivating and friendly learning environment.
- Accentuating institutional profile"

All of these positive effects make PBL an attractive curricular approach in the development of the new engineering program. Of particular interest for this research work is the improvement in the self-directed learning capability, the development of management, collaboration and communication skills, and the development of professional identity.

Of particular interest is the 2002 Danish government report that 59% of private employers prefer the PBL graduates from Aalborg vs. graduates from other non-PBL universities. The PBL graduates were identified to teamwork, innovation, and project management skills and a better ability to acquire new knowledge. The UNESCO report also references a survey conducted by Danish Industry in 2004 that showed "graduates from (Aalborg) and from another traditional university have no significant differences in professional knowledge and skills, however, (Aalborg) graduates have a visibly better performance in skills of project and people management, communication, innovation, knowledge of business and life" (*UNESCO, ENGINEERING: Issues, Challenges and Opportunities for Development*, 2010).

Despite the potential for PBL, it is not without its critiques as to its effectiveness as an educational approach. Kirschner, Sweller, and Clark (2006) critiqued the effectiveness of PBL, along with several pedagogical approaches grouped together under the category of minimal guidance instruction. Although they specifically referenced problem-based learning, their definitions and arguments are applicable to project-based learning as well.

Kirschner's and his colleagues' argument is that although minimally guided instructional methods, such as PBL, are "very popular and intuitively appealing," they ignore what is understood about human learning and evidence from studies of student learning. They argue that "direct instruction guidance" is a more effective and efficient education model.

They highlight two underlying assumptions with "minimal guidance" models. First, "they challenge students to solve 'authentic' problems or acquire complex knowledge in information-rich settings." The second assumption identified is "that knowledge can best be acquired through experience based on the procedures of the discipline." They identify, we feel correctly, that this is a constructivist instruction viewpoint of learning.

Kirschner, et al. (2006) specifically point to the need for learners to search for information in the "problem space" that is relevant to what they are supposed to be learning. They argue that this places a high load on the individual's working memory with minimal contribution to long-term memory. They define changes in long-term memory as the core aspect of the individual's learning.

To support their arguments, they cite the review work of Mayer (2004) on several studies comparing "guided forms of instruction" to "unguided, problem-based instruction." Mayer concludes his analysis of studies from the 1950's-1980's with "debate about the discovery has been replayed many times in education, but each time, the evidence has favoured a guided approach to discovery."

Kirschner, et al., conclude that "may be an error to assume that the pedagogic content of the learning experience is identical to the methods and process (i.e. epistemology) of the discipline being studied and a mistake to assume that instruction should exclusively focus on application." They argue it is time to abandon constructivism and return to more guided approaches, such as worked examples and process worksheets.

Although Kirschner does make some strong arguments regarding how individuals learn, they take a simplistic viewpoint of constructivist education methods such as problem- or project-based learning. Specifically, they err in grouping them in the category of minimally guided instruction (Hmelo-Silver, Duncan, & Chinn, 2007) with other pedagogical approaches. The 2007 rebuttal of the Kirschner, et al., article by Hmelo-Silver, et al., specifically points to the ignoring of the scaffolding of learning that can take place in problem-based learning.

Not only does scaffolding help guide the novice through the complex learning process, Hmelo-Silver et al. (2007) identify that it "may also problematize important aspects of students' work in order to force them to engage with key disciplinary frameworks and strategies." It makes the disciplinary thinking and strategies explicit. Sheppard et al., (2009) in Educating Engineers, identified the use of scaffolding within a spiral-learning model as a critical element to reforming engineering education.

Hmelo-Silver et al., (2007) point out that scaffolding also addresses the high cognitive load issue from the Kirschner (2006) argument. It also provides an authentic approach for instructors to embed their expert guidance and knowledge.

Although the Kirschner, et al., article does raise some valid concerns regarding minimally guided instruction, we argue that project-based learning, with the use of scaffolding to reduce cognitive load, embed expert guidance, and to make explicit the disciplinary thinking and learning strategies, addresses those concerns and allows for a PBL instruction model to take full advantage on a constructivist model of student learning. The arguments and evidence presentment by Hmelo-Silver (2007) appear to support this viewpoint.

An earlier review of problem-based learning by Norman & Schmidt (1992), sought to evaluate the evidence to identify if there was support for many of the claimed advantages for PBL's effect on student learning. They looked at the specific claims of increased student motivation; problem solving skills; ability as self-directed learners; ability to learn and recall information; and ability to integrate knowledge into actual application.

They identified that there was sufficient support for PBL in the literature to increase students' motivation and abilities claimed. A review of experimental evidence to support each claim was conducted. Norman and Schmidt concluded that:

> *"(1) there is no evidence that PBL curricula results in any improvement in general, content-free problem-solving skills; (2) learning in a PBL format may initially reduce levels of learning but may foster, over periods up to several years, increased retention of knowledge; (3) some preliminary evidence suggests that PBL curricula may enhance both transfer of concepts into clinical problems; (4) PBL enhances intrinsic interest into clinical problems; (5) PBL appears to enhance self-directed learning, and this enhancement may be maintained."*

In this review, they identified key components to a PBL curriculum:

- Students benefit from working through the problem versus a rote fashion
- Students receive immediate corrective feedback regarding incorrect concepts

The critiques do point out the need to focus on some key curricular aspects in development of the new PBL programs. First, there is a need for scaffolding with embedded expertise to reduce the potential for too high a cognitive load for students. The scaffolding should make the learning of disciplinary thinking and strategies explicit. Second, students benefit from struggling through the problems or projects, but immediate corrective feedback is needed regarding incorrect concepts if students are to take advantage of the PBL instructional approach.

It is clear that there is tremendous possibility with a PBL curriculum to support student learning and provide them with the abilities that are desired by industry. Next the PBL curricular elements will be developed, which will serve as the framework for the curricular decision that will be made in the curricular development.

2.4.5. FRAMEWORK FOR CLASSIFYING - PROJECT-BASED LEARNING AND CURRICULAR ELEMENTS

A PBL curriculum model has been developed that creates a framework, which is based on PBL learning principles and curriculum theories of alignment and social construction (Kolmos, de Graaff, & Du, 2009; Savin Baden & Wilkie, 2004; Savin-Baden, 2003, 2007), for understanding an existing or developing a new PBL curriculum. The seven curricular elements of the model are shown in Figure 2.15:

- objectives and outcomes,
- types of problems, projects, and lectures
- progression, size and duration,
- students' learning,
- academic staff and facilitation
- space and organization, and,
- assessment and evaluation (Kolmos & Graaff, 2014)

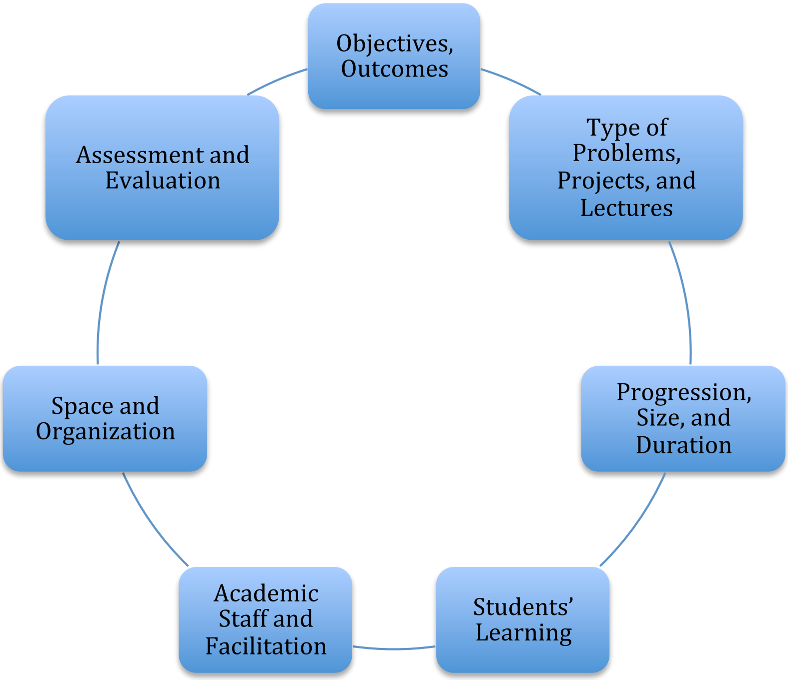


Figure 2.15. PBL Alignment of elements (Kolmos, de Graaff, & Du, 2009)

Each of the elements of this PBL curricular model has a broad spectrum from "a teacher-controlled on the one side to an innovation and learner-centered approach on the other side" (Kolmos & Graaff, 2014). Between each of the ends of this spectrum are several degrees of varying, mixed approaches that can be applied in the development of a PBL curriculum. Kolmos and de Graaf note that the "principle of alignment is an underlying assumption." A change in one element has an affect on all of the other elements as they are holistically aligned to facilitate the student learning of the program objectives and outcomes. Each of the elements will be described and the characteristics of each spectrum end identified. They will be used in Chapter 3 to characterize and analyze the Iron Range PBL model and in Chapter 4 to describe and analyze its process of development.

<u>Objectives & Outcomes</u>

With any curricular model, it is essential to identify the objectives of the curricular model; defining what the curriculum is trying to accomplish; and what knowledge or learning outcomes there are for graduates of the program. Defining and agreeing upon the learning objectives for the program is a critical part of the vision-casting of the change process described in Section 2.2. The 2011 Royal Academy of

Engineering study of curriculum change identified defining the outcome elements as a critical part of the successful change processes (Graham, 2012b).

The spectrum for this element begins on the *discipline and teacher-controlled approach* end; it is expressed by learning objectives being very specific to the discipline itself. The knowledge content is, also, focused solely on that content that is pertaining to only the discipline itself (Kolmos, de Graaff, Du, et al., 2009). This is contrasted with the *Innovative and learner-centered approach* for this element, which focuses on interdisciplinary knowledge and methodological approaches associated with PBL (Christensen, Henriksen, & Kolmos, 2006).

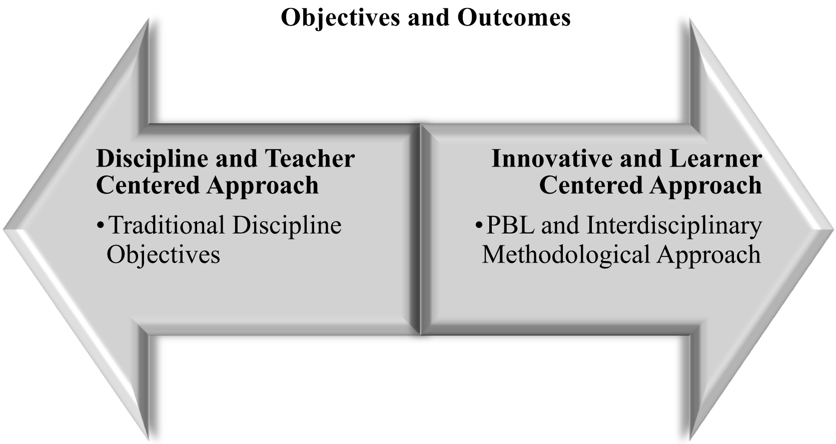


Figure 2.16. Objectives and outcomes spectrum

Types of Problems, Projects, and Lectures

The types of problems, projects, and lectures that students experience, and on which they practice, relates directly to the curricular objectives and graduate outcomes. In the *discipline and teacher-controlled approach* part of the spectrum, the closed-ended problems are well defined with specific steps to a solution and a specific answer. At the other end of the spectrum is the *Innovative and learner-centered approach.* Here, projects are ill-defined, leaving both approach and final solution to be determined by the teams and their students. These types of projects support the interdisciplinary approach of PBL.

Lecturing is part of the whole spectrum; however its focus, content, and duration adjust based upon the type of problem and project work students are doing. In the *discipline and teacher-controlled approach,* lectures focus on knowledge transfer from the expert to the student. In the *Innovative and learner-centered approach,* the lectures need to support the project. The emphasis shifts from knowledge transfer to guiding students through the knowledge acquisition process, as directed by their project work.

Types of Problems, Projects, and Lectures

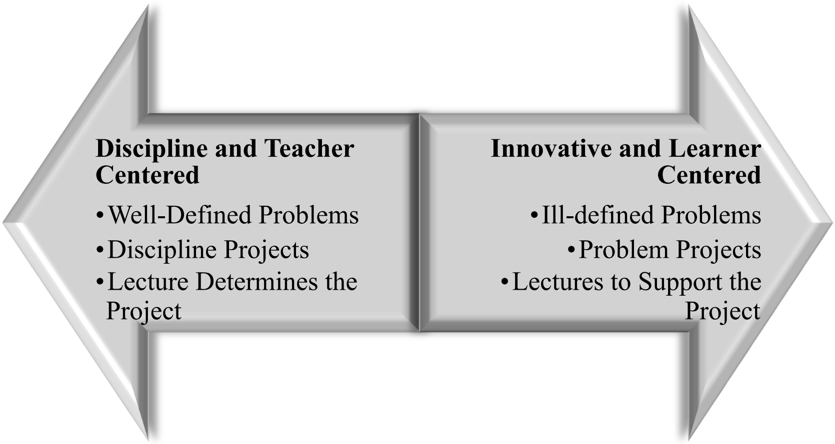


Figure 2.17. Types of problems, projects, and lectures spectrum

Progression, Size, and Duration

One of the initial characteristics of the progression of PBL is the percentage of time committed to project work or the size of the project work within the curriculum. On the *discipline and teacher-controlled approach* end of the spectrum, the project work is relegated to a minor part of the curriculum. It could be an add-on to one or more courses or serve as a capstone senior design project.

As the profession moves towards the *Innovative and learner-centered approach* end of the spectrum, the projects consume more and more time within the curriculum. As the time dedicated to projects increases, so does the impact the project work has on student learning. The learning outcomes that can be achieved in the PBL curriculum are dependent on this time commitment, as the learning takes time within the project work.

Savin-Baden (2000, 2007) proposed five models of PBL, focusing on the objective of the PBL model and the perceptions pertaining to knowledge, learning, problems, students, teacher roles, and assessment. It is not intended that one model is preferred over another; what matters is that the model that best facilitates students meeting the desired learning outcomes of the program is selected. The problem approached is at the center of the projects within the developed definition for project-based learning.

> *Model 1: PBL for Epistemological Competence* – the problem (or project) is very narrow in this model with knowledge attainment focus more or less propositional within a narrow problem scenario. This model represents the end of the project scale that is characterized by having a set or narrow problem (or project) process and final solution option.
>
> *Model 2: PBL for Professional Action* – the problem (or project) is characterized by real-life situations with a knowledge attainment focus that is practical and performance-oriented.
>
> *Model 3: PBL for Interdisciplinary Understanding* – the problem (or project) is situational with a problem scenario that requires a combination of theory and practice, with knowledge attainment focus that is propositional, performance-oriented, and practical.
>
> *Model 4: PBL for Trans-disciplinary Learning* – the problem (or project) scenario consists of dilemmas that require students to use different disciplinary knowledge. The aim of this model is to test the knowledge of the team.
>
> *Model 5: PBL for Critical Contestability* – the problem (or project) scenario is open and multidimensional in the possible focuses and approaches, with the knowledge attainment focus contingent on the project, and will be contextual and constructed by the learner for given situations.

All five models represent the variability that can exist in problems (or projects) to facilitate student learning. The commonalities are the:

- “learning is organized around problems (or projects)”;
- “problem is the incentive for the learning process and is a central principle to enhance students’ motivation”;
- “importance of problems the students are attracted to on the basis of their own experiences and interests. It could be any type of problem (or project); it could be a concrete and realistic problem or a theoretical problem”; and
- most importantly, “problem reflects the conditions of professional practice. Therefore, it makes sense that, in some instances, cases are relatively short, providing study materials for half a week, and in other instances, a project could last half a year” (de Graaff and Kolmos, 2007).

Progression, Size, and Duration

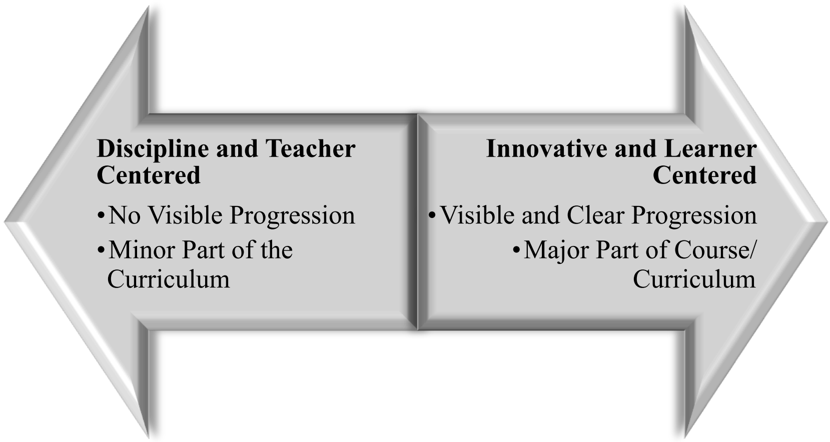


Figure 2.18. Progression, size, and duration spectrum

Students' Learning

Students generally enter their engineering curriculum with little to no experience or training for function as a team or how to manage projects. This is a critical part of the PBL curriculum; what are the expectations that the students have?

The types of problems, projects, and lectures that student experience, and on which they practice, will relate directly to the curricular objectives and graduate outcomes. In the *discipline and teacher-controlled approach* end of the spectrum, the closed-ended problems are well defined with specific steps to a solution and a specific answer. At the other end of the spectrum, in the *Innovative and learner-centered approach,* projects are ill-defined, leaving both approach and final solution to be determined by the teams and their students. These types of projects support the interdisciplinary approach of PBL.

Students' Learning

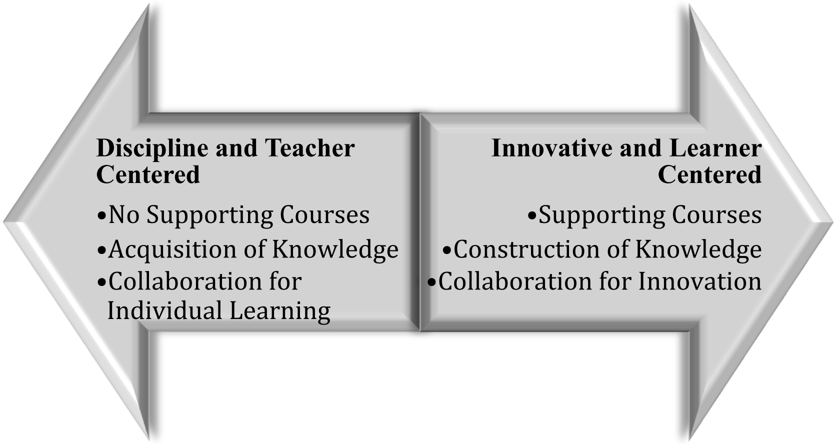


Figure 2.19. Types of students' learning spectrum

<u>Academic Staff and Facilitation Element</u>

Critical to any curricular model is the role of the academic staff in facilitating and guiding student learning. In most models of education, faculty are left, for the most part, to their own expertise and efforts to find ways to facilitate learning within the traditional lecture course model. In most cases, faculty will utilize the methods that they are familiar with from their own undergraduate and graduate experiences.

In a PBL curriculum, the model of facilitating student learning is a contrast to what they experienced in their own education. Successfully changing to the PBL curriculum is dependent on the academic staff receiving training to develop effective methodologies in facilitating the student construction of knowledge in the team or groups settings of the projects. The role of facilitator or guiding the process of the teams will be new to most, if not all of the faculty. Training will be needed for the team process to be successful. If the change to PBL is to have longevity, the change theory discussion, from earlier in this chapter, would point to this development not being a one-time event but an ongoing part of the PBL program culture.

Academic Staff and Facilitation

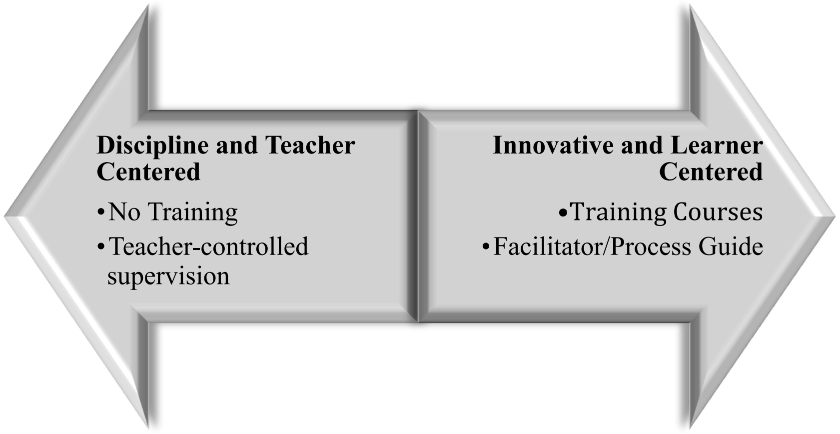


Figure 2.20. Academic staff and facilitation spectrum

Space and Organization

Just like the academic staff need training to transition to supporting the new curricular model, so does the physical space and the institution's organization (de Graaff & Kolmos, 2007). Space needs to be made available that supports the team activities. The organization needs to develop and recognize that the PBL curriculum will need to be supported in a different way than a traditional program would.

Space and Organization

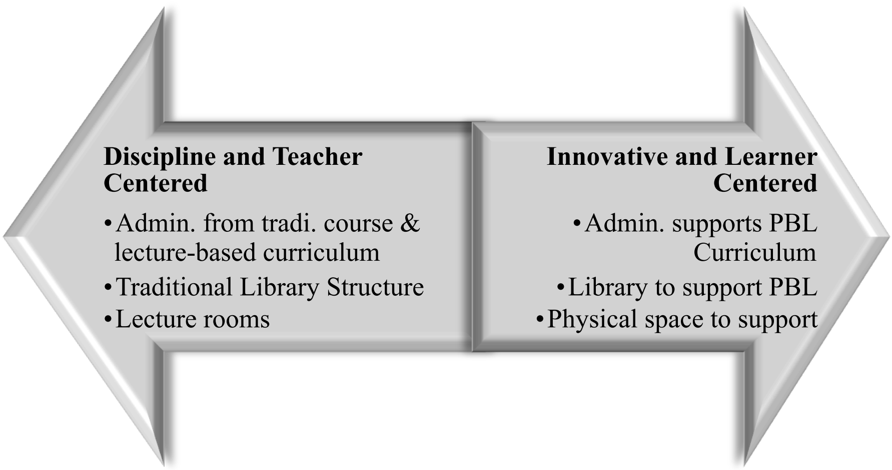


Figure 2.21. Space and organization spectrum

Assessment and Evaluation

Assessment and evaluation of student learning will need to adapt to support the PBL curriculum. There needs to be alignment between the program outcomes and the development of assessment methods that support the student attainment of the outcomes. Whether assessment is taking place on an individual or team basis is an important decision in the development of the program. As with any curriculum, whether evaluation is going to formative or evaluative is another important consideration. Student involvement in the development of the assessment and evaluation decisions is an important part of student autonomy and commitment to the new education model.

Space and Organization

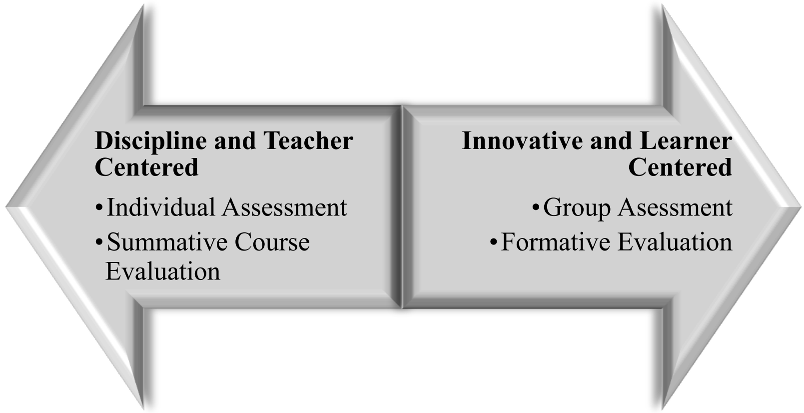


Figure 2.22. Assessment and evaluation spectrum

The purpose of this section has been to provide a theoretical framework for a PBL curriculum. The principles of PBL have been described and placed within the learning theory. The curricular elements have been identified for the development of the PBL curriculum. In subsequent chapters, the framework will be used in describing the Iron Range Engineering model of PBL.

***Key Finding*: This spectrum-based framework will be applied to analyze the Iron Range Engineering model in Chapter 4. It also creates a taxonomy structure for analyzing and comparing PBL curricular models. The intent is to not rank models in comparison to one another but to provide individuals involved with curricular change decisions a way to better understand different curriculums as PBL is applied in different social and education contexts.**

2.5. CONCLUSION

Chapter 2 has developed the change, curriculum, learning, and PBL theoretical perspectives that serve as the basis for the development and implementation of the Iron Range Engineering program. The Organization Change Model and Curriculum Change Model provide both a process for overall organizational change and for a curricular change to PBL. The curriculum perspective was considered from three viewpoints (curricular structural elements, a classification framework, exemplary curricular) to develop an extensive set of curricular criteria to be used in developing the new PBL curriculum. The learning theory perspective has been developed to use Illeris' triangle, the APA principles, and the elements of learning and learning environments in describing PBL and the Iron Range Engineering model of PBL. The PBL theory was explored to identify the curriculum elements for the development of the Iron Range Engineer PBL program.

Chapter 3 will develop a historical description of the development and implementation of the PBL curriculum. The change theory perspective will be used to analyze this process. Chapter 4 will describe the current program and analyze it within the learning, curricular, and PBL theoretical perspective developed in this chapter.

CHAPTER 3. HISTORY

(RON ULSETH AND BART JOHNSON)

3.1. INTRODUCTION

The idea of the Iron Range Engineering program began in the early 2000's as a dream and progressed to the present day as the program was invented, developed, adapted, and evolved. The narrative is viewed through the lenses of two perspectives, the 8-step model for change (Froyd et al., 2000), along with the dual layers of educational change from the curricular and organizational viewpoints (de Graaff & Kolmos, 2007). These models were discussed in Chapter 2 and provide a perspective through which to analyze the history of the Iron Range Engineering program.

3.2. ITASCA COMMUNITY COLLEGE

Iron Range Engineering had its beginnings in Itasca Community College; a lower-division engineering program. In the United States, a four-year bachelor of science engineering degree is split between lower division, the first two-years and first 64 credits, and upper division, the second two-years and final 64 credits. The first two years are primarily focused on foundational science, math, and general education courses with some focus on introductory engineering courses. It is not until the second two years, the upper division, that students truly enter an engineering program such as mechanical, electrical, chemical, biomedical, etc. The first two years have been referred to as the "math-science death march" (Goldberg, 2014). The attrition of students in the models is staggering; approximately 40% of students who start with engineering in their first year of college will ultimately complete a bachelor's degree in engineering (Department of Education, 2009).

Students can either complete their lower-division learning at a university or they may choose a two-year community college. In community colleges, students earn an associate's degree and then transfer to a larger four-year university to complete the bachelor's degree. Community colleges are a substantial segment of the pathway to students completing a bachelor's degree in engineering. Roughly 50% of practicing engineers attended a community college on their educational pathway to becoming an engineer (NSF, 2015).

It is with this background that the Itasca Community College engineering program story begins. Itasca is a small, rural, two-year community college. In 2015, Itasca enrolled approximately 1000 full-time students (itascacc.edu, 2015). It is located in the town of Grand Rapids (~15,000 residents), in northern Minnesota in the United

States of America, approximately 80 miles northwest of Duluth. It was founded in 1922 and has held accreditation with the North Central Association Higher Learning Commission since the mid-1970's. The institution primarily serves students located in the northern third of the state. ICC is a member of the Minnesota State Colleges and Universities system, as well as a member of the Northeast Minnesota Higher Education District.

In the 1980's, the college had few engineering students taking math and science courses with the intent of transferring those courses, in the above-mentioned fashion, to a regional four-year university that had an engineering program of interest to them (Ulseth, 2004). Itasca physics instructor Aaron Wenger identified that there had to be a better way to instruct future engineers than the model that existed at that time.

As other faculty joined Aaron, the program grew from 10 students in 1993 (Ulseth, 2004) to a nationally recognized program (National Academy of Engineering, 2005), with well over 150 students in 2010, learning in a progressive learning community model (Johnson, et al., 2011). The authors joined the faculty of Itasca's engineering program in 1992 (Ulseth) and 2004 (Johnson).

The success of the ICC engineering program was based on six main program elements (Johnson, et al., 2011). These elements each focus on developing students to be successful in their upper-division program, and more importantly, in their engineering careers. It is these elements and this success that served as the baseline philosophy and experiences that enabled the authors to start the Iron Range Engineering program. The six elements are described in detail below.

3.2.1. STRONG RELATIONSHIPS WITH FEEDER PROGRAMS

Itasca developed a two-prong strategy for building strong relationships with regional K-12 students, teachers, and schools. The first prong was cultivating an overall student interest in the field of engineering through high school visits and hosting regional engineering events. The second prong was focused on developing personal connections with students from these high schools before they started their college academic careers. The connections built a trusting and cooperative relationship between students and their future college instructors. This created a foundation for student success that helped with the transition from high school to college and then continued, as the students progressed to their four-year transfer institutions and into their early careers.

3.2.2. DESIGN AND PROFESSIONALISM SPINE

Itasca developed a two-year engineering and professional development (EPD) course sequence to focus on developing the students as engineers and professionals. This course sequence focused on:

- Student Development - Each semester students learned and practiced the skills needed for success in college and the profession. Example topics were time management, study methods, stress management, personal health, personal finance, and fitness. This component of the four-course EPD sequence was focused on increasing the level of student efficacy, which is positively related to student academic success and adjustment during the first year of college (Sheppard, et al., 2009).

- Engineering Development – Students practiced engineering in an increasing level of sophistication each semester. Students learned the project management and teamwork skills needed to successfully integrate their engineering knowledge into practical application.

- Professional Development – Students developed the professional skills of ethics, etiquette, interviewing, giving presentations, “dressing for success,” and interpersonal communication as an integral part of the EPD sequence. Graduates of the Itasca program frequently referred to the positive impact the professional development activities had on their experiences as interns and, ultimately, in their careers.

- Citizen Development – Students learned that, as engineers, their career role was one of being a servant to society. Students developed this identity through presentations, reading activities, and completing a minimum of 70 hours of community service. Examples of the activities included road-side cleanups, recreational trail maintenance, teaching science and engineering activities at local elementary schools, and volunteering at the local food-shelf, Habitat for Humanity, animal shelter, and homeless shelter. Through these experiences, a culture was fostered in which these future engineers developed as individuals that make an active difference in the communities in which they live.

This four-course EPD sequence provided students with the professional practice needed to prepare them as future engineers “who are both competent and attuned to the full range of demands and possibilities inherent in the professional practice of engineering” (Sheppard, et al., 2009).

3.2.3. ACTIVE FACULTY AND STUDENT LIFE

The Itasca learning community had a very active faculty *and* student life component with multiple activities focused on developing strong working relationships between faculty and students that enhanced the student learning in the classroom and improved student retention rates. The program had developed into a family of learners – students, faculty, and staff – which recreated together, socialized, learned, and interacted on a 24/7 basis. The elements of the program included many different student/staff/faculty sub-communities within the larger community (Johnson & Ulseth, 2011):

- "Approximately 100 engineering students lived in the engineering housing facilities. This living community incorporated weekly events and additional mentoring experiences. Pike, Schroeder, and Berry (1997) related persistence to success in residential learning communities.

- Several learning community events placed faculty and students together in a setting outside of the classroom. Events such as camping trips, basketball leagues, engineering Olympics, Itasca engineering triathlon, Pi(π) run, and hotdog roasts at faculty members' homes were key elements of the relationship building that made Itasca unique.

- The learning community supported interest in specific clubs with significant student and faculty participation: science café, outdoor adventure club, chess club, engineering modern dance club, engineering acting, curling club, a basketball league, etc.

- At any time during the year, there was a planned engineering learning community-wide event being executed. Examples included: Saran-wrap canoe contest, cribbage tournament, fishing contest, spaghetti feed, Yahtzee tournament, cross-country skiing, and much more.

- Several times per year, organized transfer trips were taken via motor coaches during which students and faculty visited the engineering programs at the regional engineering universities.

- There were multiple "plant-trips" per year that brought students to industry settings where they learned more about the different disciplines of engineering."

All of these activities built relationships and enhanced the quality of interaction between students and faculty. Braxton, et al., (1997) and Tinto (1998) related persistence to completion and quality of student-faculty interactions. The level of student-faculty interactions and the student connection to the engineering learning community at Itasca improved the quality of student learning and increased the level of student success in the completion of a four-year degree.

3.2.4. BLOCK SCHEDULING OF COURSES

For many engineering students who start at a community college or who are "second tier" students (Felder, 1993; Sheppard, et. al., 2009), the calculus math sequence is a key factor in their completing an engineering degree, and influences the length of time to their graduation. This is due, in part, to the math prerequisites traditionally required for engineering and physics courses. In order to finish a bachelor's engineering degree in four years, a student must start Calculus 1 in the fall of the first year and then successfully complete all required math and STEM courses on the first attempt and in a specified order. If any of these conditions are not met, the students face a one-semester or one-year delay in starting or completing an engineering education.

Itasca developed its block scheduling as one potential solution to provide more flexible academic pathways (Johnson, et al., 2011). Math, science, and engineering courses at Itasca were taught in eight-week block class format instead of the traditional 16-week semester format. Students generally took two engineering, math, or science classes per eight-week block, while completing one or two semester-long general education courses. Each block class is scheduled for two hours per day, five days a week with flexibility for the instructor to provide a "float" or non-contact day each week for student work days or engineering program events. The format of two eight-week blocks per semester provided students with the opportunity to catch up to their "Calculus 1 ready" peers in their STEM courses and stay on track to complete their degree in four years. A student could start the semester in Pre-Calculus, finish it in the first eight weeks, and then finish Calculus 1 in the last eight-week block of the semester. The model addressed a multitude of scenarios for math course sequences, which could cause a delay in the completion of an engineering degree in four years, such as a student's starting math course, performance in a particular course, and potential scheduling issues such as full courses.

In addition, the block schedule allowed students to pursue academic interests such as study abroad programs and co-op learning experiences, and come back to school and readily catch up to their peers. Each year, about 10% of Itasca's engineering students participated in a student exchange program with Svendborg Technical School in Denmark. Due to the block schedule, these students were able to participate in this eight-week study abroad program with no impact on their time to graduation.

3.2.5. ACTIVE LEARNING STRATEGIES

The flexible 5-day, 2-hour class format also enabled a better setting to create an active student-learning environment. The engineering program's math, chemistry, physics, and engineering faculty were dedicated to meeting Educating the Engineer 2020's call for engineering education to "address how students learn, as well as what they learn, in order to ensure that student learning outcomes focus on the performance characteristics needed in future engineers" (National Academy of Engineering, 2005). The faculty focused their efforts on studying and adapting the latest in the knowledge of engineering education. This led to further study and application of active student learning methods or problem- and project-centered learning, lab-centered instruction, modeling eliciting activities, academic journaling, etc. into the curriculum to help students attain the skills, experiences, and knowledge necessary for success in their engineering education and, ultimately, their engineering careers. An important step along the pathway toward project-based learning was Itasca's involvement in the EPICS program, founded at Purdue University. EPICS utilizes engineering design in the context of service learning in local community service (Coyle, Jamieson, & Oakes, 2005). The key components of EPICS design projects are service, academic content, partnerships/reciprocity, mutual learning, and reflection (Lima & Oakes, 2014). The ideals of EPICS aligned with the experiences desired in the EPD sequence. The focus on reflection turned a new page in our pedagogical approaches that would last deep into the development of the IRE model to the point that reflection became a core value of the program.

3.2.6. STRONG ARTICULATION AGREEMENTS WITH REGIONAL FOUR-YEAR INSTITUTIONS

Dimitriu and O'Connor (2004) identified that one of the elements vital to "recruiting and retaining students in a community college engineering program and preparing them to be successful after transfer to a four-year university" was to "increase coordination of curriculum between community colleges and four-year universities by obtaining articulation agreements with surrounding area institutions" (Dimitriu and O'Connor, 2004). Itasca had developed strong working relationships and articulation agreements with the several regional engineering programs. This led to the relationship that would evolve with Iron Range Engineering.

Figure 3.1 shows a mapping of these 6 curricular elements of the Itasca Community College engineering program.

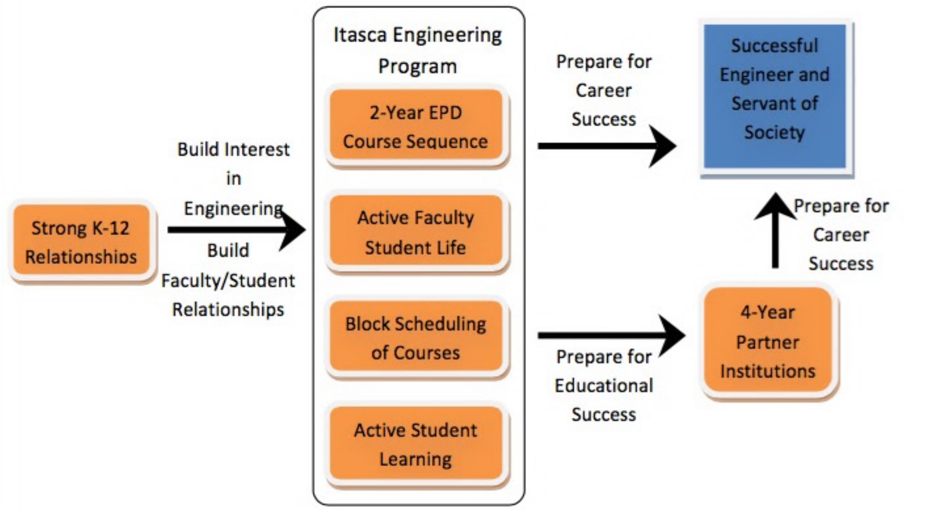


Figure 3.1. Elements of Itasca Engineering program model (Johnson & Ulseth, 2011)

This model created a learning experience with a demonstrated level of success for the diverse body of second-tier students starting their learning in the community college pre-engineering program. At the time that Iron Range Engineering began to be developed, students were completing their engineering bachelor's degree in an average of 8.8 semesters with graduation rates of 49% for all students who start the program and 67% for students who start with or achieve a "Calculus 1" math ability during their college education (Johnson and Ulseth, 2011). Itasca's 49% and 67% degree completion rates compared well with the degree completion rates of other institutions and studies (note that most students entering the comparison institutions would be starting with Calculus 1 as a first math course):

- 40.8% national engineering/engineering technologies degree completion rate from a U.S. Department of Education study (2009).

- 69% 6-year graduation rate for engineering students at Michigan Technological University, a transfer institution for Itasca students (Provoast, 2011).

- 56% 6-year graduation rate for incoming fall 2001 engineering students at the University of North Dakota School of Engineering and Mines, a transfer institution for Itasca students (Osowski, 2011).

- 45% male and 49% female graduation rates for incoming fall 1996 students in a 2005 study of the Southeastern University and College Coalition for Engineering Education (SUCCEED) Institutions (Borrego,

> 2005). SUCCEED institutions award over 1/12 of all U.S. engineering degrees and includes Clemson University, Florida A&M University, Florida State University, Georgia Institute of Technology, North Carolina A&T State University, North Carolina State University, University of Florida, University of North Carolina at Charlotte, and the Virginia Polytechnic Institute and State University at the time of the study.

Despite this level of innovation and success in creating a learning experience that helped students in their academic success, there was always a frustration in the experiences that students had at their transfer institutions (Kreck, 2013). Despite the national and international calls for change in engineering education, the students were still receiving a very traditional model of education in the upper-division programs into which they were transferring. It is in this context that a small group of prime-movers at Itasca Community College began to dream about change and set an initial vision. It is at this point that the Iron Range Engineering chapter begins in the history of this engineering educational change.

3.3. ORGANIZATIONAL CHANGE MODEL

The history of the Iron Range Engineering program can be analyzed through each of the 8 steps of the organizational change model.

3.3.1. ESTABLISH NEED AND ENERGY FOR CURRICULAR CHANGE

The need for curricular change came from national and international calls for change in engineering education (Ulseth, Froyd, Litzinger, Ewert, & Johnson, 2011; Kreck, 2013; Ewert, Ulseth, Johnson, Wandler, & Lillesve, 2011), dissatisfaction by leadership team in national responses to the calls for change (Cole, 2012a; Ulseth & Johnson, 2014; Ulseth & Johnson, 2015), dissatisfaction with the student upper-division experience after they left Itasca Community College's lower-division program (Kreck, 2013), misalignment of the student learning experience with the intended graduate outcomes (Ulseth & Johnson, 2015), and a regional need for work-force and economic development (Cole, 2012b; Ulseth, Froyd, et al., 2011). A small group of prime-movers at Itasca Community College in Grand Rapids, Minnesota [insert map of MN] began to dream about change and set an initial vision. These prime-movers provided the energy for curricular change from the inception in 2003 (Cole, 2012a) through development and implementation to present day.

3.3.2. GATHER LEADERSHIP TEAM

The original direction came from the small group of Itasca Community College faculty members. This group sought outside guidance from a variety of sources in engineering education from across the U.S. through a small planning conference in

2003. From that planning conference emerged a group of five members that would steer the direction, develop and evolve the model and seek funding (Cole, 2012a) over the next five years. In April 2009, funding was approved for the initiation of the program (Ramsay, 2011; Office, 2009). At this point, the original members of the steering committee sought a highly regarded set of leaders from U.S. engineering education to guide and advise the program's development. This national advisory board included: Jeffrey Froyd (Texas A&M), Sheri Sheppard (Stanford), Tom Litzinger (Penn State), Denny Davis (Washington State), and Ed Jones (Iowa State).

In addition to the national advisory board, the program leaders quickly developed relationships and sought leadership from local industry, state legislators, the funding agency, university leaders, and local college leaders. Program partnerships are shown in Figure 3.2.

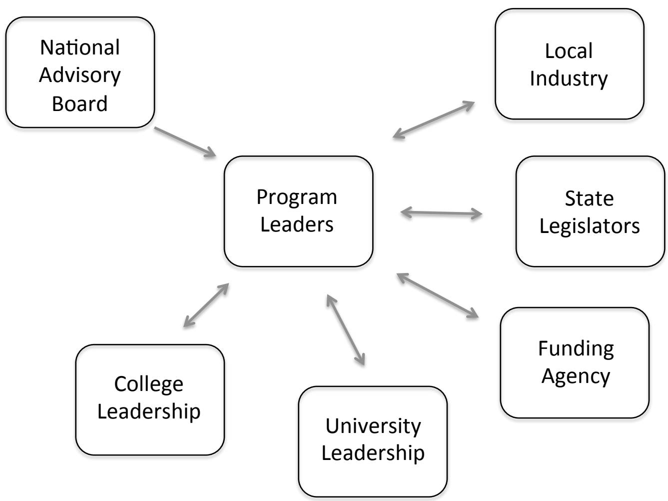


Figure 3.2. Program partnerships

3.3.3. NEW OBJECTIVES AND LEARNING ENVIRONMENT

The new advisory board provided much direction for the program leaders as the program developed with immediacy, as the curriculum would be delivered only 9 months after funding. The national advisory board developed the program's first set of program educational objectives (see Figure 3.3) and pointed the program leaders to Aalborg University. Program leaders visited Anette Kolmos in Aalborg in November 2009. This meeting and the Aalborg model provided the leaders a framework for project-based learning on which to attach the myriad of curricular ideas they brought forward from the 6 years of curricular innovations. The initial curriculum delivered in January 2010 was this adaptation of the Aalborg model (Ulseth & Johnson, 2015). The learning environment development took place over several years of evolution between 2009 and 2014.

The program educational objectives for Iron Range Engineering are listed below and have been published on the official IRE website. They are consistent with the Iron Range Engineering Program Mission to serve northern Minnesota. Graduates will achieve at least two of the following objectives, but will be capable of achieving all within one to four years of graduation:

1. Designing, implementing and integrating thermal, electrical, mechanical, and computer-controlled systems, components, and processes that will serve the region, the nation and the world.
2. Continuing their education through technical or professional graduate programs, professional licensure, or certifications, and the wide variety of other types of life-long learning.
3. Creating, developing, leading, and managing in a wide range of enterprises that result in sustainable and enhanced economic regional development through their disciplinary expertise.
4. Demonstrating actions such as community service, professional ethics, professional responsibility and mentoring future engineers.

Figure 3.3. Iron Range Engineering program objectives

The learning environment from a physical sense was initially dictated by the space available for the program as tenants on the local college campus. Each year from 2009 to 2013, the available space changed and grew until, in 2013, a new facility, funded and designed specifically for the program, was opened (Ramsay, 2013). The important aspects for the physical learning environment were space for project teams to collaborate, space for learning conversations between students and academic staff, space for students to construct physical models and prototypes, and community gathering space. Through each evolution of the physical learning environment, the quantity and quality of these spaces increased.

The other qualities of the learning environment that were specifically developed, and then refined over time, were a highly collaborative nature among students, teams, and staff (Arendt, 2014), and a major emphasis on the development of professional responsibilities and skills, self-directed learning abilities, and design thinking.

3.3.4. DISCUSSION OF THE NEW OBJECTIVES AND ENVIRONMENT WITH THE COLLEGE

The program leaders were implementing a program that was a collaboration between a two-year community college and a four-year university (Arendt, 2014). The community college district was the fiscal owner of the program and provided the tenancy. The university owned the degree granting, the curriculum, and the majority of the teaching staff. The physical location of the program was 200+ miles from the university. There was a dichotomy in the relationships between the program and the collaborative institutions. The community college district gave the program great autonomy over fiscal decisions and environmental decisions; whereas, the university engineering departments and college were quite restrictive and frequently objected too much of the pedagogy and curriculum. Allendoerfer, et al. (2015) thoroughly studied and documented this change process. The result of the situation was that the program leaders advanced the deployment of the curriculum through the PBL pedagogy using the objectives and outcomes from the national and industry advisory boards. The university ultimately approved the curriculum nearly two years after it was first implemented.

3.3.5. IMPLEMENT THE NEW CURRICULUM

In January 2010, the pilot curriculum began. The elements of the curriculum evolved almost daily. By the end of two semesters, it had taken a recognizable shape. In Appendix D, the authors described the pilot curriculum at the end of one year of implementation. The first year pilot was characterized by industry-provided, ill-structured, project-based learning. The professional, design, and technical learning domains were integrated and focused on the project. Attributes of the learning environment included oral exams, deep learning activities (DLA), reflection, and metacognitive analyses. Further student evaluation was based on Bloom's modified taxonomy (Ulseth et al., 2011).

3.3.6. EVALUATION

The Iron Range Engineering model of continuous improvement is thoroughly summarized in Chapter 4 of this thesis. The model provides for a periodic evaluation of internal and external input on the strengths and weaknesses. The evaluation is followed by the creation of new goals or modification of previous goals and the establishment of an action plan for the implementation of the goal (Bates & Ulseth, 2013). From the very first year, the program regularly invited visiting experts to spend time immersed in the model; observing student and staff learning activities and interviewing students, staff, and industry partners. While the number of external visits, by a wide variety of experts from across engineering education, numbered 2-4 per year, one group of external advisors visited regularly. They made four visits between 2010 and 2015. Their reports provided a longitudinal view of the evolution of the program. Their first visit, in early 2011, provides insight into the strengths and the weaknesses of the pilot implementation. The members of the visiting team across the time span were Rose Marra, University of Missouri (all four visits), Carolyn Plumb, Montana State University (3 visits), David Jonassen, University of Missouri (deceased, 1 visit), and Betsy Palmer, Montana State University (deceased, 1 visit). The first report was submitted in April 2011 and serves to evaluate the pilot implementation of the IRE model (Jonassen, Marra, & Palmer, 2011). The program refers to the series of reports as the Marra-Plumb reports.

The external evaluation of the pilot model raised several issues that would need to be addressed in future evolutions of the model (Jonassen et al., 2011):

- Students and staff had an inadequate understanding of the purposes and uses of Bloom's taxonomy. The hierarchy associated with taxonomy was translated as a way to assign grades to students, putting a lower emphasis on areas within the taxonomy that were important for student development.

- Related to the taxonomy issue, evaluation of student learning was misaligned with the goals of student learning.

- Highlighted in the first evaluation, and continually addressed well into the program's development, was the connection between technical learning of competences directly related to the project vs. competences not related to the project (Marra & Plumb, 2012; Marra & Plumb, 2013). This stems from the curricular requirements for graduation (http://cset.mnsu.edu/ie/ire.html). By these requirements, students need 32 upper-division technical credits in their last four semesters for graduation. Of the 32, 16 are prescribed, and 16 are elective. In a given semester, a student completes 8 technical credits. The first evaluation highlighted high levels of student motivation and interest in those of the 8 that were most directly related to the semester project, and inadequate learning in the others. Over the next five years, program staff would attack this problem from a variety of ways until it was mostly mitigated by the 2015 Marra-Plumb evaluation (Marra & Plumb, 2015).

- Metacognition was identified as an important aspect of the IRE curriculum (Jonassen et al., 2011). Students were metacognitively reflecting on all aspects of their professional, design, and technical learning. However, students and staff were operating under a limited view of the concept. Recommendations were made to institute a metacognitive training program to "support the kinds of learning and problem solving required by IRE, including more work on task types, methods for assessing personal comprehensions and ability to solve different levels of learning, and application of alternative strategies that can be applied" (Jonassen et al., 2011). Here again, several years of development and continuous improvement brought the program to a higher level of operation: "we think that, for now, a very effective set of activities (immediate reflection, end-of-semester metacognition memo, and the Professional Development Plan) is in place, and no changes should be made" (Marra & Plumb, 2015).

- An essential element of PBL is students working in teams. The first evaluation highlighted issues with the program and its ability to support students working in teams. Two big issues were highlighted. First, was regarding students migrating to their own areas of expertise and thus not getting experiences in the areas where they most needed development. The second issue was that traditional gender roles were being assigned within teams. For example, women often were assigned roles relating to organization and communication, whereas men would be doing fabricating such as welding. The first issue was addressed through improved training of facilitators. The second issue ultimately resulted in the program hiring external consultation on gender diversity analysis and training. Several tools have been developed for IRE to use with students and staff on an ongoing basis to focus on inclusion (Bogue & Marra, 2015).

- Another element of the IRE model is the use of oral exams for all technical learning. This is unique in that the norm for technical learning is the use of written examination. It is an adaptation the developers made from the Aalborg model. Raised as an issue in the evaluation of the pilot implementation, was an inconsistency in the deployment and evaluation of oral exams by academic staff. During the pilot implementation, there were very few developed rubrics for any evaluation. The external evaluators noted this. They recommend rubric development for oral exams (Jonassen et al., 2011).

The pilot implementation was seen internally by staff and students and externally by visitors from engineering education as "particularly strong in helping students to develop lasting technical, design, and professional competencies associated with the industry based problems they [were] solving" (Jonassen et al., 2011). It was this sense, a sense that the vision dreamed of by the early leadership team had a good chance of being realized, that kept a high level of optimism in light of the obvious needs for improvement identified in the first Marra-Plumb report.

3.3.7. IMPLEMENTATION PLAN

The implementation team was guided forward at each juncture by the model for continuous improvement described in Section 4.5. As the pilot concluded, the future implementation plan resulted from a reaction to the external and internal inputs for improvement. Plans were made and implemented on a semester-by-semester basis. The program adopted an OAR (Observation, Action, Result) method to track changes. The implementation of the IRE model deviates slightly from the organizational change model in that the organizational change model is geared towards changing a larger college, where the results of the pilot would be converted to a plan for a larger implementation. At IRE, the continuing iterations of the model were all focused on the one program.

3.3.8. PREPARING FACULTY

The institutionalization of the approaches took place as the new semesters brought new groups of students and additional faculty members. New faculty and students were prepared to enter the model through orientation sessions at the beginning of the semester. Orientation workshops included new members of the community along with the returning members. Many details were provided on how the project, technical, and professional learning activities would be deployed. Each week, the learning community of students and staff would start with a two-hour seminar to provide grounding, connecting weekly activities to the overall goals of the program. Faculty met once each week for two hours to address how to meet students' needs across the three learning domains. These weekly sessions were how faculty were prepared for the new implementations and how new approaches were institutionalized into the model.

3.4. CURRICULAR AND ORGANIZATIONAL CHANGE

In Section 2.2, the two-layer model (de Graaff & Kolmos, 2007) is described. Viewing the history of Iron Range Engineering through the organizational change model in Section 3.3 and again from this two-layer perspective provides a more complete view of the model and its history.

3.4.1. CURRICULAR LAYER – STUDENTS

The funding of Iron Range Engineering as a new model of engineering education came from the Iron Range Resources and Rehabilitation Board, an agency of the state of Minnesota in April 2009 (Ramsay, 2013). The $1.2 million one-year budget came with the expectation that the program would deliver curriculum to students in the upcoming academic year. Program staff had not yet been hired, the national advisory board had not yet been formed, and the Aalborg model of PBL had not yet been identified. Starting the program in August 2009 was out of the question. There are two semesters in a college year in Minnesota. To meet the funding requirement of delivering curriculum and having enough time to organize and make decisions meant a start date of January 2010.

While one important aspect of implementing a new program is the curriculum, equally important is having a student body. The 2009 graduating class of Itasca Community College, students completing the first two years of their 4-year bachelor's degree, were given the opportunity to join Iron Range Engineering as the first generation of students. 14 students stepped forward and took a leap of faith that their engineering education could be more valuable in a new model that was yet to be identified than it would be in one of the traditional engineering programs they would have otherwise entered. Figure 3.4 is a photo of the Generation 1 students.

Figure 3.4. IRE Generation 1 students

The students were hired as interns during fall semester 2009 to assist in program development. They started the curriculum in January 2010 and were the subjects of the pilot program. The IRE model of continuous improvement (see Figure 3.5) includes regular input from students. The Generation 1 students provided critical input throughout the entire four semesters of their education. They were exposed to rapid change and, as a result, had to acquire a skillset of flexibility and adaptability.

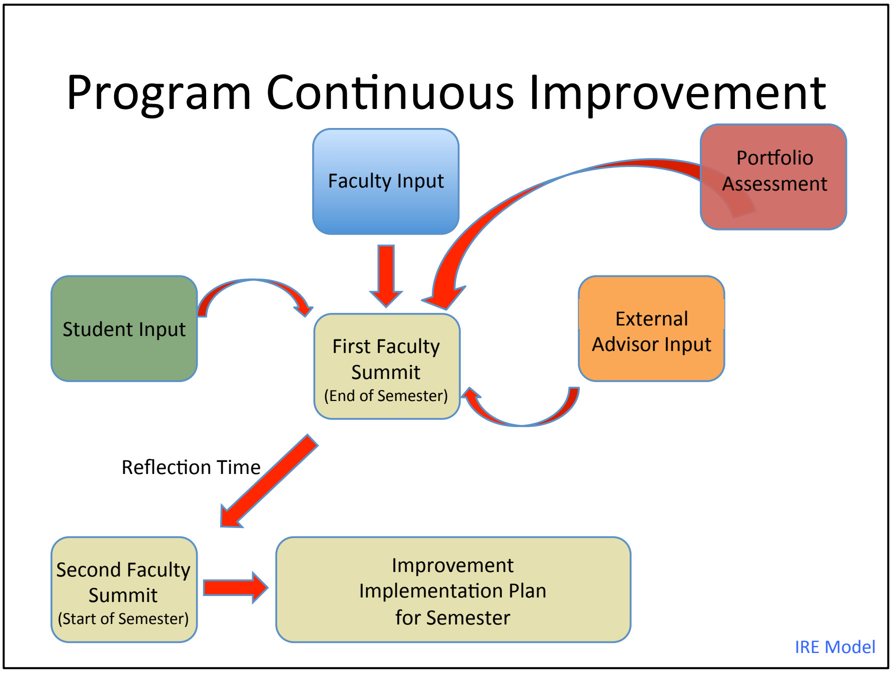


Figure 3.5. IRE continuous improvement model

All 14 students succeeded to graduation (Ramsay, 2011). The program is indebted to the group for their risk taking, trailblazing, and success (Ramsay, 2011). Figure 3.6 is a photo of the granite plaque permanently mounted to the wall in the Iron Range Engineering building.

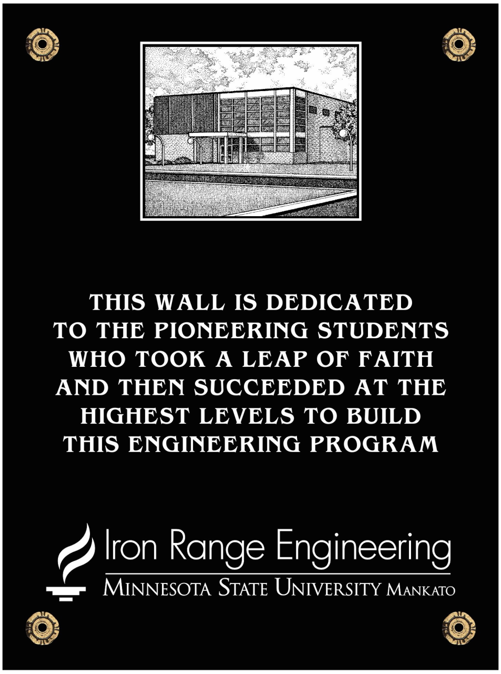


Figure 3.6. IRE plaque dedicated to early students

Attracting students to the program was hampered by the demographic conditions (low population) of the region, the new/unique/unproven nature of the program, and the fact that the program was not yet ABET accredited. However, each semester, new students enrolled. Table 3.1 shows the enrollments and graduates by the timeline.

Table 3.1. Iron Range Engineering enrollments

Semester	**Starting Generation (# of students)**	**Graduating Generation (# of students)**
Spring 2010	Gen 1 (14)	
Fall 2010	Gen 2 (10)	
Fall 2011	Gen 3 (23)	Gen 1 (14)
Spring 2012	Gen 4 (4)	Gen 2 (8)
Fall 2012	Gen 5 (8)	
Spring 2013	Gen 6 (16)	Gen 3 (20)

Fall 2013	Gen 7 (8)	Gen 4 (3)
Spring 2014	Gen 8 (13)	Gen 5 (7)
Fall 2014	Gen 9 (9)	Gen 6 (14)
Spring 2015	Gen 10 (10)	Gen 7 (8)
Fall 2015	Gen 11 (20)	Gen 8 (13)

The graduates were welcomed to industry for their new skillset. They achieved high levels of initial employment (Cole, 2012b). They have demonstrated high levels of satisfaction with the skills they brought to industry and their employers consistently rate them higher than their peers in performance (Ulseth & Johnson, 2015). The culture of the student body evolved over time from pioneering in the beginning to professional workplace in the present day. Currently, the culture is characterized as mature, thoughtful, and professional (Marra & Plumb, 2015).

3.4.2. CURRICULAR LAYER – FACULTY

During the first pilot semester, when there were 14 students, there were two faculty members, Dan Ewert, and Ron Ulseth. Ewert and Ulseth were engineering educators with more than 20 years of teaching experience each. They were members of the original team of dreamers from the early 2000's and were each highly motivated, by personal experience, to develop a new model of engineering education. Ewert had a background in electrical engineering and biomedical engineering. Ulseth had a background in mechanical and civil engineering. Both had industry experience, Ewert as the CEO of a startup company and Ulseth as a licensed professional engineer who practiced engineering in the U.S. Navy Reserve. Ewert and Ulseth served the program and the students in many roles. They directed the program externally by communicating with the advisory boards, funding agency, the colleges, and industry partners. Internally, they developed the curriculum and delivered it to students as the project facilitators, technical competency instructors, and advisors. There was one staff member in addition to the faculty members. He provided administrative support, coordinated student life, and assisted project teams access equipment and supplies. By the second semester, two new faculty members were added, a master's level electrical engineer and a retired practicing professional engineer. The electrical engineer provided technical expertise for students acquiring technical competence and facilitated a project team. The professional engineer served on an adjunct basis as a project facilitator. As time went on, the academic staff continued to have these components; full-time PhD engineers, masters/bachelors-level engineers, and professional engineers from practice. Table 3.2 shows the evolution of the faculty over time. In addition to teaching faculty, the program has had non-teaching staff members provide crucial administrative support, technology support, laboratory management, and student life activity support.

Table 3.2. Iron Range Engineering academic staff

Year	PhD	Masters/Bachelors Full-time	Professional Engineers Adjunct
2009	1	1	
2010	1	2	1
2011	2	2	1
2012	3	3	1
2013	3	3	1
2014	3	3	2
2015	3	3	3

While Ulseth and Ewert entered the academic staff with decades of engineering education experience, new instructors and facilitators were very new to engineering education, often joining the faculty to begin their career as educators. Ewert would leave the program after 2010. Ulseth remained to the time of PhD defense as the director of the program and a full-time instructor and facilitator. While not regularly on the ground as a full-time instructor, PhD student Bart Johnson played a role from the beginning. He served as an initial dreamer, an architect of the initial program, has served in the role as technical instructor of learning competencies, and 2013 - 2015 was the Chief Academic Officer at Itasca Community College and thus supervisor of the program's director.

The full-time faculty, from the beginning, served dual roles as technical instructors and project team facilitators. The nature of both the learning and instruction were different than the staff members had encountered in their prior experiences as either students or instructors. When a new member joined the faculty she or he knew they were coming to a PBL model where teaching and learning were different, and they were hired because of their desire to join the model. However, serving in the new roles required a paradigm shift. No longer were they expected to be an expert who possessed all of the knowledge and then transmitted to the students, but rather they became learning coaches and role models and team mentors. The acquisition of these abilities happened in real-time on the job. Each week from the program start in 2010, one or two hours were dedicated to faculty development of facilitation and instruction skills. In these sessions, faculty members discussed obstacles and successes they were encountering in their daily facilitation and instruction roles. They coached each other and strove for continuous improvement.

Evaluation issues regarding faculty were identified in the Marra-Plumb reports. Students were concerned about faculty being spread too thin (Marra & Plumb, 2012). The external evaluators were concerned about the faculty environment not being conducive to tenure (Marra & Plumb, 2013). Students and evaluators were concerned about the lack of consistency among instructors in how syllabi were implemented in technical learning (Jonassen et al., 2011; Marra & Plumb, 2012; Marra & Plumb, 2013; Marra & Plumb, 2015). As time went by, some of these faculty issues were resolved. For example: "Faculty are available in person, by phone, by e-mail – almost any time... Faculty are receptive to student feedback, and they respond to it" (Marra & Plumb, 2013). Other issues continued to persist, such as the consistency of faculty noted above in all four reports.

3.4.3. CURRICULAR LAYER – GOALS

The goals of the program at its inception can be seen in the poster in Figure 3.7. Ulseth and Johnson presented this poster at the ASEE Global Symposium in Singapore in 2010 in the midst of the pilot implementation of the model. Specifically, goals were (Ulseth & Johnson, 2010):

- Deliver new-look engineer with high levels of employability skills
- Student-centered curriculum and learning activities
- Industry-driven project-based learning
- Regional economic impact through engineering workforce development
- Integrated technical, professional, and design competences
- High motivation, self-directed learning environments

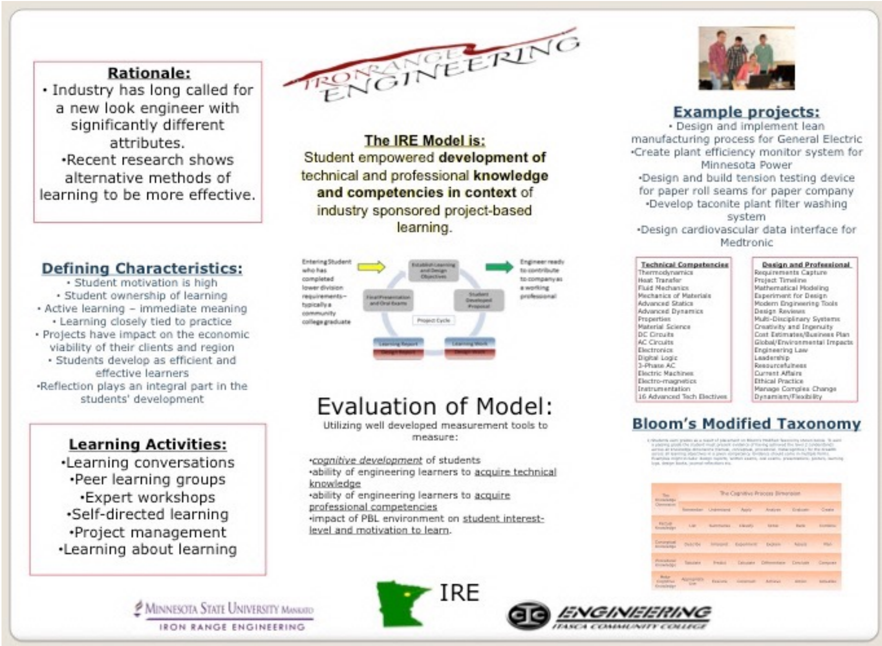


Figure 3.7. Poster Delivered in 2010 signifying the goals of Iron Range Engineering at program inception (Ulseth & Johnson, 2010)

The goals in 2010 are reflective of what the dreamers had in mind in the early 2000's (Cole, 2012a) and what was being delivered in 2015 (Lord, 2014).

3.4.4. CURRICULAR LAYER – SELECTION OF CONTENT

The program was conceived and designed to deliver a bachelor's degree in engineering so that graduates could enter the workforce. As an upper-division only program, the lower-division requirements were the same as any engineering student transferring to a traditional engineering program. Content selection thus was limited to upper-division programming. The three domains of content are described in detail in Chapter 3. They are design, professionalism, and technical competence. Figure 3.8 is a text box showing the description of the curriculum as it was designed, approved by the university curriculum process, and communicated to ABET in 2012 (Bates & Ulseth, 2012). Figure 3.9 is a graphical representation of the curricular content selected by the program (Bates & Ulseth, 2012).

> The Iron Range Engineering B.S. in Engineering program is implemented each semester with a 15-credit load comprised of six courses of the types listed below:
>
> 1. Design (3 credits) – an industry-based engineering project addressed by a team of IRE students

2. Professionalism (3 credits) – independent study of core professional competencies that include learning and leadership, team work and communication, and professionalism and ethics
3. Seminar (1 credit) – exploration of contemporary engineering issues and wide variety of professional practice topics with external professionals and peers
4. Mechanical Core Competencies (e.g., 3 credits) – individual study of core ME competencies
5. Electrical Core Competencies (e.g., 3 credits) – individual study of core EE competencies
6. Advanced Engineering Competency (e.g., 2 credits) – individual study of advanced competencies related to design project and career interests

Figure 3.8. Curriculum Description (Bates & Ulseth, 2012)

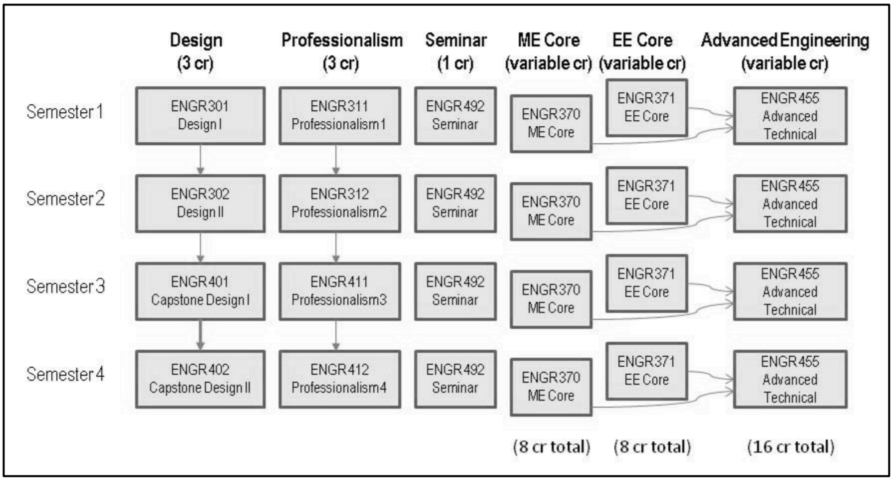


Figure 3.9. Graphical depiction of Iron Range Engineering content (Bates & Ulseth, 2012)

3.4.5. CURRICULAR LAYER – TEACHING AND LEARNING METHODS

The Aalborg Model of PBL served as the inspiration for the teaching and learning in the Iron Range Engineering program (Kreck, 2013). Central to the Aalborg model are project teams being facilitated by faculty project supervisors (Kofoed et al., 2004) in a dedicated group project space. The IRE developers adopted this model for the initial curriculum implementations in 2010. The project team, group room, project facilitator model remains unchanged and unmodified six years later, at the time of the publication of this thesis. Also adopted from the Aalborg model is the concept of process analysis, "The objective of process analysis is for the students to develop awareness of the work-and-learning processes, in order to become better project workers. Completion of the process analysis, which involves the student in documenting his/her reflections of the project process, has been a requirement in the (Aalborg) Basic Study Program since 1982" (Kofoed et al., 2004). The adaptation of process analysis at Iron Range Engineering extended beyond the project to the processes of personal, professional development through the PDP (professional development plan) and to technical competence learning through the metacognitive memos.

Departure from the Aalborg model came as developers looked to conceive a new model for technical competency teaching and learning. The original faculty members and students created the concept of the "Learning Conversation" during the pilot implementation. The philosophy behind learning conversations (see Section 4.4) was to have students access information between conversations and then bring questions to the discussion with their peers and teachers. Focus was put on conceptual understanding of fundamental concepts, in contrast to a focus on solving closed-ended problems using the fundamental concepts, as was prevalent in traditional engineering programs. The deliverable components of the technical competency were documentation of learning from personal learning and learning conversations, a deep-learning activity in which students used process learning to perform a "hands-on" activity, a metacognitive memo reflecting on the learning processes used and evaluating the effectiveness of the learning processes, and an oral examination focused on explaining the fundamental concepts and their application to the project.

3.4.6. CURRICULAR LAYER – ASSESSMENT

Curricular assessment in the Iron Range Engineering model happens at the program level and the individual level. The story of the IRE continuous improvement model for program level curricular assessment is described in Section 3.5 and alluded to in previous sections of this chapter. Student assessment, at the time of program implementation, was focused on the formative development of the individual in the technical, professional, and design project domains with the inclusion of team formative assessment in the design project domain.

Formative assessment took place within learning conversations as faculty members gave developmental feedback on the acquisition of knowledge of the fundamental engineering principles under study. Summative evaluation took place at the end of the technical competency as students were graded on the quality of their deliverables, which included documentation of technical knowledge gain, problem sets, deep learning activity reports, oral examinations, and metacognitive memos. As the program matured through the semesters and feedback came from the external evaluators, the importance of improving the quality of the formative feedback and being consistent in the summative evaluations was continuously highlighted and remains a need for the program at the time of this publication.

In the professional domain, the assessment was highly focused on formative feedback. The individuals were empowered to adopt a model of continuous personal improvement. In their first semester, students self-evaluated on a continuum of novice to expert their abilities and attributes in several professional development areas such as communication, leadership, teamwork, etc. Their project facilitators provided feedback to assist the students in calibration of their own impressions. At the end of each semester, the students reflected on growth and re-evaluated on the continuum giving evidence of the new assessment. Upon completion of the evaluation, they set goals for future improvement and developed action plans for implementation to move towards achievement of the goals. Again, students were given feedback by project facilitators. This cycle of personal, professional improvement continued through each of the four semesters of the students' education. The focus was on the formative growth though grades needed to be assigned at the completion of each semester. Students were given these summative evaluations based on the quality of their documentation of continuous improvement, rather than on an evaluation of how well the goals were met.

3.4.7. ORGANIZATIONAL LAYER – ORGANIZATION AND CULTURE

The culture at Iron Range Engineering has been characterized in the above sections. In this section, more attention will be given to the organizational structure and obstacles. IRE is a collaborative program. The two curricular partners are Itasca Community College and Minnesota State University, Mankato. The institutions are located 200 miles apart. A third collaborative partner, Mesabi Range College located 60 miles from Itasca and still 200 miles from Mankato, houses the Iron Range Engineering program. In a sense, the IRE program started as a "green-field" physically dislocated from the organizations and cultures that were its institutional "owners."

Allendoerfer studied the change process at IRE and presented the paper, "Leading a Large-Scale Change in an Engineering Program" (Allendoerfer et al., 2015), at the ASEE Annual Conference and Exposition in 2015. Her work highlights the tensions as the program was, in a way, resented by the engineering departments at the collaborative institutions for different reasons at each campus. The philosophical beginnings of the program were at Itasca. By leaving the Itasca campus, there was a feeling of loss, a feeling that the program belongs here, so why is it at Mesabi Range? The reason for the location of the program on the third campus was one of funding. The leaders of the funding agency funded the program to reside at that location.

The feelings of resentment from Minnesota State University had two main roots. Whereas, at Itasca, the program was a bottom-up development, at Mankato there was very much a top-down "force-feeding" of the program from the university president to the engineering college in the short period described earlier in this chapter, from an idea being funded in April 2009 to its commencement in January 2010. The cause for resentment came from the PBL pedagogy. The department curricula and teaching and learning methods were being taught in the traditional method. The idea of PBL was seen as an affront to their way of delivering engineering education.

Allendoerfer interviewed all of the critical members involved in the startup of Iron Range Engineering. She interviewed the "dreamers" from Itasca, the faculty at Mankato, the IRE leaders, the politicians who funded IRE, the college and university deans, provosts, and presidents who were involved, and a consultant who negotiated the memorandum of agreement between the two institutions establishing the partnership. Figure 3.10, borrowed from Allendoerfer et. al. (2015) shows the organizational relationship at the startup of the program.

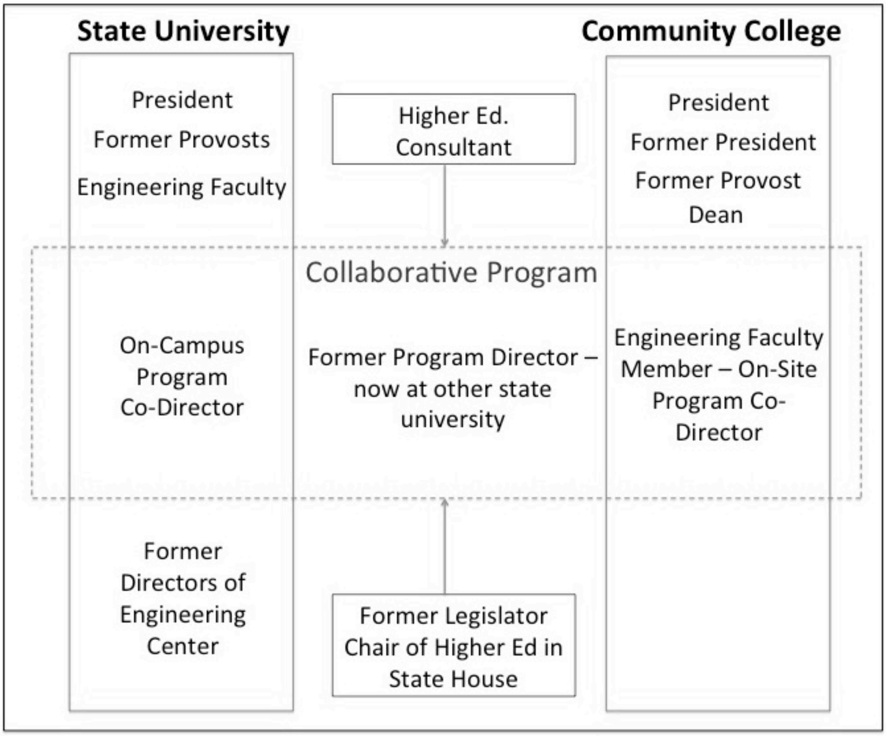


Figure 3.10. Organization and relationships at start-up of Iron Range Engineering. (Allendoerfer et al., 2015)

Identified in Allendoerfer's study were critical attributes of the change process and critical junctures in the process (Allendoerfer et al., 2015). An important event in the story of Iron Range Engineering occurred in early 2011. The program was into its third semester. Students on campus were on pace to graduate in December of that year. The PBL model at Iron Range Engineering was evolving on the trajectories described in earlier sections of this chapter. However, things on the Minnesota State University, Mankato campus were not going well. Ewert and Ulseth would travel to Mankato to try to get the degree and program courses approved by college and university curriculum committees. They were met with complete resistance.

> "I remember one time in a Curriculum Committee meeting we were going to explain, before we dropped the curriculum off on them, what the philosophy was. … Ulseth went to that meeting and I had him speak because they had known him. I was new, so I wanted him to [speak]. Well, then they saw him as being at Itasca Community College telling them how to educate engineers at a university. We're a community college; they're a university. Oh my gosh. One guy stood up and…yelled at us and he goes, 'This is just a ploy by community college to take over engineering education!' No." *Former Program Director – Ewert* (excerpt from Allendoerfer report)

In an attempt to end the impasse, the university president called a summit of leaders from the college, the university, and the program. The critical decision came when all parties agreed on putting in place a leader from Mankato's on-campus engineering college. The person selected was Dr. Rebecca Bates. Bates was able to understand the potential of the PBL pedagogy and understand the concerns in the college and work with both parties to find a path forward.

> *"The value is hiring the faculty there, but also having faculty back on the campus so the linkage, you know, in this case, and I think one of the reasons things went so well is because Becky was here. And people liked her. They knew her; they trusted her. She kept them informed on what was going on. And so long as we can continue with that, I think we're going to be fine. But if we ever get out of the loop from the main campus I think there could be some concerns." State University President* (excerpt from Allendoerfer report)

Bates was able to get the curriculum and degree approved. She has served the program as on-campus co-director ever since, acting as the liaison between the program and the university.

The summary of findings from Allendoerfer et al. (2015) includes the necessity of having champions at all levels, creating new organizational "boxes" or strategies to overcome obstacles, and identifying translators in key bridging positions (such as Bates). The works of Allendoerfer et al. have resulted in NSF funding to translate how these findings can be of value to other organizations looking to make similar curricular change.

3.4.8. ORGANIZATIONAL LAYER – VALUES AND CONCEPTUAL CHANGE

Iron Range Engineering exists more as an individual entity that emerged rather than as a part of an existing organization that underwent change. From this perspective, we analyze how the values of the program and its developmental trajectory emerge rather than how the values and developmental trajectory of an existing organization empower change within the organization.

The values emerged from the "dreamers'" desires to meet the international calls for change in engineering education. Those international calls are embodied in the National Academy of Engineering's Engineer 2020 (National Academy of Engineering, 2004). The attributes of the Engineer 2020 were not aligned with the learning activities undertaken by students in traditional engineering programs. The values of the Iron Range Engineering program emerged as developers sought to achieve that alignment. Alignment would come from students acquiring the professional employability skills needed to perform in their engineering careers, the ability to perform as self-directed technical learners, and from learning activities that aligned with the knowledge of how people learn. Restating, the values of the IRE program were to provide a learning environment where students could (Ulseth, Johnson, & Bates, 2011):

- Acquire professional employability skills
- Acquire self-directed learning abilities
- Learn, using techniques aligned with the emerging knowledge of how people learn

The conceptual change or developmental trajectory of the program emerged as an embodiment of the model of continuous improvement embraced by the program. Figure 3.5 shows how the program systematically evaluates itself each semester.

Described in previous sections, the model of continuous improvement extends beyond the program to the students in their development and the academic staff in their development. The program has a culture and a mindset of continuous improvement. This mindset defines the developmental trajectory of conceptual change.

3.4.9. ORGANIZATIONAL LAYER – PHYSICAL SPACE AND RESOURCES

The story of acquisition of resources and physical space provide the last piece in the narrative of Iron Range Engineering through the perspectives of organizational and educational change. Kreck (2013) in Figure 3.11 and Cole (2012a) in Figure 3.12 detail the elements of how Iron Range Engineering got funding. The key player in the story was a passionate state representative in the Minnesota legislature, Tom Rukavina. He had dreamt for years about bringing engineering education at the bachelor's level to his rural district. See the story in the text box below.

Reprinted (with permission) from Education Commission of the States
November 2013

"Iron Range Engineering – The third in a series of papers on rural education issues"
by Carol Kreck

Tom Rukavina, who now works for U.S. Representative Rick Nolan, was a Minnesota legislator for 26 years. "My district produced 60% of all the iron ore mined in Minnesota. Because of federal law, our land grant college, the University of Minnesota, received land and mineral rights. Just by chance, the land they received with the mineral rights contained iron ore. And over the last 100 years, the university has gotten millions of dollars from the mining companies that bought their ore," Rukavina told ECS.

Those millions went into a permanent fund as required by federal law with the interest going to research. This all happens in the Minneapolis/St. Paul area, and Rukavina worked for years to try and shift some of the money back to the Iron Range for higher education.

So Rukavina took a different path. "You see our mines pay a production tax in lieu of property taxes." The tax gets distributed to northeastern Minnesota schools, cities, and towns through a state economic development agency, the Iron Range Resources and Rehabilitation Board (IRRRB). "The production tax goes up each year … usually around 5 cents a ton of taconite, unless the legislature decides to freeze it."

In 2008, as house chair of higher education, he took that escalator and directed it to the IRRRB for higher education. At the time, with 40 million tons of taconite produced annually, that amounted to $2 million a year.

Also at the time, Rukavina met Ron Ulseth, a professor of engineering at Itaska (Itasca) Community College in the Range who had an idea for a new kind of engineering school, a purely hands-on program that would be based at a local community college. It was the kind of program that had been recommended in *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, published by the National Academy of Engineering, part of the National Academies, in 2005.

Figure 3.11. Education Commission of the States (Kreck 2013)

Thus, there was a regionally located, state agency capable of educational funding and a desire by some people to use this funding for engineering education. In parallel, the IRE group of dreamers were searching the country for funding opportunities to pilot their new ideas. In the text box below, Cole tells the story of how the two groups came together.

Reprinted (with permission) from Hometown Focus Newspaper April 2012
"No One Does Engineering Like the Range"
by Jean Cole

"I started dreaming about how to do it better across the four years. I talked to people all around the country. I could envision a better way," Ulseth said. "For a couple of years, from 2005-2007, (We) tried to get funding, but there was no interest."

But Sertich (college president), Rep. Tom Rukavina of Virginia, and others were interested in somehow offering a four-year engineering program on the Range, and started exploring the possibilities in 2008. "I was skeptical," said Ulseth, "because I couldn't understand why anyone would choose to come here for the same old, same old."

By this time, Ulseth's son was a sophomore in high school and planning to become an engineer. "I didn't want to send him off for a 'hollow' experience," said Ulseth. "It was really bothering me." Then comes the "deer stand story."

"It was the last week of deer season: I was sitting in my stand. I was thinking to myself, 'Sertich wants this. Rukavina wants this. We have the same goal. We have different ideas how to get here, though. But then the light bulb came on. I thought I saw the way. I sent a text to Mike (Johnson, Provost of ICC). He was sitting in his deer stand, too. I told him, 'We can do it. Let's get everybody together for a meeting.'"

A meeting was set for the following Tuesday. "Monday night I sat down with some construction paper, it was red, I remember, and I made a Power Point presentation. This was November of 2008. After several more meetings, by (April) of 2009, we received funding from the IRRRB."

Figure 3.12. Hometown Focus April 2012 (Cole, 2012a)

Initiated in 2009 was a funding stream for Iron Range Engineering. It provided $1 million annually for staff, scholarships, operating expenses, and equipment and continues to do so to the present day (Iron Range Resources, 2010). This is an unusual funding pathway. Most funding in Minnesota public higher education comes in a direct allocation from the state. This is still public money but is money dedicated to the region in lieu of property tax income from the iron mining companies. This is how the educational change requirement for the organization was met.

The history of physical space follows a similar trajectory. In 2009, the program moved into a small section, in a corner of Mesabi Range College in Virginia, Minnesota. By the fall of 2010, as the Generation 2 students were starting, more space was needed. Again, the college provided space. During this timeframe, Representative Rukavina was seeking state capital bonding for a facility for the program. The bonding bill passed in 2010, only to be vetoed by the outgoing governor. In early 2011, in fact, on the day after the critical summit called by the university president to solve the collaboration stand-still (described previously), the new governor of Minnesota came to IRE to learn about the program. He was so impressed by the students and the model, he walked away claiming "your new building will be in my budget proposal by tomorrow." As the session ended, the governor and the legislature were at a standstill. The state government was shut down for several days. In the negotiations to end the shut-down, the governor passed a bonding bill that included a $3 million allocation to build learning space for Iron Range Engineering. In 2013, the facility opened with 10 new "group rooms" for project teams and major laboratory space for project manufacturing, modeling, and testing. The building has officially been named the "Tom Rukavina Engineering Center" (Bily, 2014), as pictured in Figure 3.13 at the dedication ceremony.

Figure 3.13. Dedication of the Tom Rukavina Engineering Center

3.5. SUMMARY OF IRE HISTORY

The history of Iron Range Engineering is a narrative that emerged from dissatisfaction with status quo and as a dream of a few for a new future of engineering learning. That dream of a few turned into the work of many (see Figure 3.14) who empowered the implementation of a new model of engineering learning.

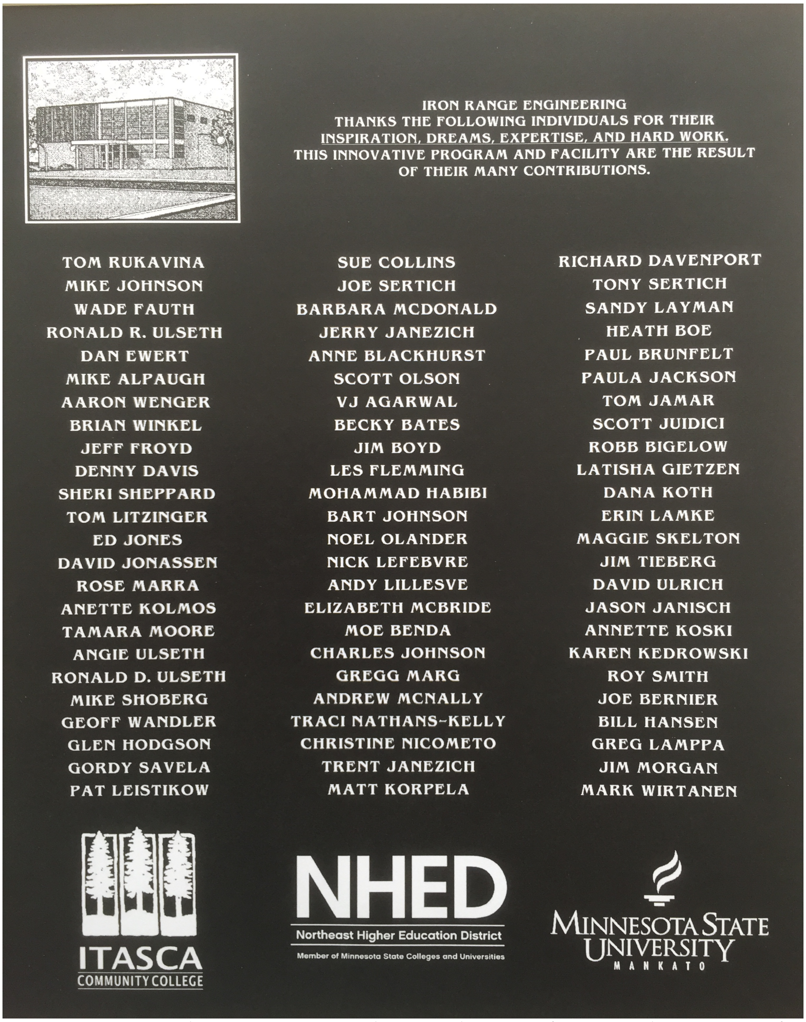


Figure 3.14. Granite plaque recognizing the contributions of many to the creation of to IRE

The underlying theme, repeated again and again, is one of continuous improvement. A mindset in which the successes of today are appreciated and the needs of today turn into a plan for improvement of tomorrow. The 2015 Marra-Plumb report highlights the story of IRE through its successes (Figure 3.15) of the present day and the needs for improvement (Figure 3.16) for the future. See text boxes below, (Marra & Plumb, 2015).

Highlighted Program Strengths in May 2015, (Marra & Plumb, 2015).
"Here are some observations about the many positive aspects we observed and that were reported:

- Nearly all students commented that they are learning more about "professionalism" than they would in a traditional program—and they appreciate that.
- During previous visits, we sometimes heard about concerns from students regarding how prepared they would be technically. Students, once they are in the program, do not seem to have that concern now.
- The program appears to have achieved an appropriate balance between structure and providing needed supports for students.
    - This is particularly true in the area of metacognition where you have adjusted the requirements for metacognitive memos without apparently diminishing the impact of metacognitive development.
    - Describe sheets used for preparing for Learning Conversations are also well received, as well as the first semester seminar.
- In contrast to past visits, it appears the active Gens of students had realistic expectations of IRE on their arrival. They appear, overall, to be satisfied with the level of structure versus self-directedness.
- Assessment of learning, both oral and written, appears to be perceived as consistent by students; this is a definite positive change from past visits.
- Faculty are quite available in person, by phone, by e-mail—almost anytime.
- Most students voiced positive feedback about the group forming process—putting new students into a group with "experienced" students and, in some cases, letting students choose their own groups.
- Many students continue to perceive that what they are learning is "sticking" better than learning in a more traditional program.
- There has been a marked improvement in lab training and lab management procedures (see section below), which appears to have resulted in labs being a more comfortable and accessible environment for all.
- The Professional Development Plan seems to have strong support from students.
- Students report that the climate is collaborative rather than competitive—there is a sense of community
- A lot of learning continues to happen among peers.
- The program continues to have good relationships with industry partners."

Figure 3.15. Successes from Marra Plumb report

Highlighted Program Needs for Improvement in May 2015 (Marra & Plumb, 2015)

Recommendations: Learning Conversations

- Provide at least some faculty with more structure to be successful in their Learning Conversation implementations— for instance help in forming list of topics and a proposed schedule that is published to students.
- Have faculty discussions to help standardize the enrollment size of Learning Conversations. Some students reported that larger groups > 6 or 8 made it difficult for the Learning Conversation to actually be a "conversation." We note that more experienced faculty may have the ability to effectively keep a conversation "feel" even for larger groups.
- Implement a systematic mechanism for student anonymous feedback regarding the instructor, and formative feedback during the Learning Conversation 8-week period. (see tool being developed by Bogue and Marra) and use this feedback to make mid Learning Conversation adjustments.
- Create standards that are adhered to for Learning Conversation syllabi. As one student commented: "Sometimes, with some faculty, it starts ok, then it unravels. Loses its structure. They need more planning up front. They know what needs to be taught, but not necessarily how they are going to teach it—or in what order. The presentation is not structured enough. Some faculty go too deep into first outcomes, then give short shrift to later outcomes. Faculty need to keep more on schedule."
- Strive for consistent expectations (across faculty) in Learning Conversations.
- Continue to work on both instructor and student understandings and implementations of "student directed." Although instructors should be encouraging student participation, they should not allow students to monopolize or derail the progress of other students.

Recommendations: Metacognition

- The program has had some changes in instructors the last couple of years. The level of understanding of the theory and research about metacognition amongst instructors may not be clear, and / or consistent. It might be valuable for faculty to have a more thorough understanding of metacognition: declarative vs. procedural, control vs. monitoring, etc. This might be addressed in a "faculty circle" periodically.

Recommendations: Student expectations

- Consider taking proactive steps to counteract some of the negative buzz prospective and current students hear; IRE is too new; you won't get a

job; you won't learn enough technical content; IRE is only for mining or if you want to stay in the range. • Students who are not focusing on EE / ME are sometimes still struggling to put together meaningful programs and finding expertise. Perhaps find such students – e.g. "environmental," a professional mentor, one who could help guide such a student; almost serve as a PBL facilitator for that student as he or she works through competencies that are not in expertise area of IRE faculty. Might need to pay such a person.

Figure 3.16. Needs for improvement from Marra Plumb report

3.6. ANALYSIS OF THE CHANGE

The history of Iron Range Engineering has been viewed through the perspectives of organizational change and management of educational change. The IRE model is one of both bottom-up and top-down change. Bottom-up in its creation as a new entity in northeastern Minnesota and top-down in its creation as a department in the College of Science Engineering and Technology at Minnesota State University, Mankato. The success of the start-up is evidenced by the continued existence and current vibrancy of the program. Section 2.1 of this thesis identifies and describes essential attributes for change to succeed. Table 3.3 below connects the essential attributes and how those attributes emerged in the IRE story.

Table 3.3. Connecting elements of change to Iron Range Engineering history

Essential Element of Change	**Iron Range Engineering**
Need for both external and internal drivers	-External: legislature, governor, funding agency -Internal: university and college leadership, program leaders
Leadership team	Ewert, Ulseth, Bates
Vision casting	-Alignment of engineering education activities with skills needed in profession -Regional workforce development -Alignment of learning activities with learning science
Empowering people to act	-University and college leaders empowered the program leaders to design and implement the program

	-Program empowered faculty and students to learn and succeed
Formative evaluation	IRE model and culture of continuous improvement

Key Finding: The analysis of the change and the identification of these elements for the IRE change add to the knowledge of change in engineering education. These elements are critical to the change accomplished and can be used in consideration of change within other engineering programs in the U.S. and add to the knowledge of change in engineering education.

3.7. CONCLUSION

The purpose of this section was to describe and analyze the Iron Range Engineering program. The historical context provided in this chapter aims serves to establish why did the Iron Range Engineering program start and the Iron Range Engineering program evolved. The people who lived it wrote this history. They bring biases impacted by years of investment and experiences to these descriptions. In an effort to mitigate these biases, published accounts of the history are referenced frequently throughout. This chapter should be viewed as the historical analysis of the Iron Range Engineering program as experienced by the program developers and implementers. A counter perspective could be written as a result of a case study done by an impartial observer. Both perspectives could then be of value to those wishing to learn from the history of the program.

This Iron Range Engineering narrative is a set of accounts. It is an account of continuous improvement; it is an account of educational change; and it is an account of people, their dreams, and their willingness to take risks and persist. PBL is a social construct. It is embedded in the people and the place of its existence. The authors are often confronted with the question: "is this model transportable?". The answer is no. It is a function of its people, its time, and its place. However, by describing all of the theories, components, and contexts, a knowledge base for others to contemplate is provided. Just as was done by the developers of Iron Range Engineering when they visited Aalborg University in 2009, curricular decision makers in other contexts can review, adopt and adapt the aspects of the IRE model that do fit in their program.

A better question is what curricular components of the IRE program can be transferred and adapted to different social settings, as occurred in the adaptation of element of the Aalborg model in the development of IRE. The next chapter will evaluate the PBL curriculum and it's curricular elements that can be considered, evaluated, and adapted to other education settings.

CHAPTER 4. NEW PBL CURRICULUM

(BART JOHNSON AND RON ULSETH)

The 2011 study of curriculum change by the Royal Academy of Engineering (Graham, 2012a) identified that successful change processes involve the entire curriculum structure being developed with the curriculum goals in mind. The structure must be interconnected and coherently support the change being made.

In this chapter, the program curricular structure will be described and analyzed two different ways. First with the seven curricular elements of the PBL curriculum model identified by (Kolmos, de Graaff, & Du, 2009), shown in Figure 2.14:

- objectives and outcomes,
- types of problems and projects,
- students' learning,
- progression and size,
- academic staff and facilitation,
- space and organization, and,
- assessment and evaluation (Kolmos et al., 2014)

Each element will be used to provide a brief analysis using the spectrum developed in Chapter 3. The spectrum for each element begins on the *discipline and teacher-controlled approach* on one end and then transitions to the *innovative and learner-centered approach* on the other end. The IRE PBL model will be analyzed by identifying its placement on each curricular element spectrum. Upon placement on each spectrum, the characteristics of the IRE PBL model for that element will be described in detail to create a robust description. The elements will be connected to the learning theory from section 2.3, as appropriate.

Upon analyzing the model through the PBL elements in sections 4.1 through 4.7, the analysis will continue, in section 4.9 through classifying it with the theoretical approaches from Chapter 2. The chapter will conclude with the defining characteristics of the IRE PBL curriculum to create a concise description of the curricular model.

4.1. PROGRAM OBJECTIVES AND OUTCOMES

The program objective and outcome element spectrum has the *discipline and teacher-controlled approach* on one end; it is expressed by the learning objectives being very specific to the discipline itself. The knowledge content is, also, focused solely on that content that is pertaining to only the discipline itself (Kolmos et al., 2014). In contrast, at the other end of the spectrum, is the *innovative and learner-centered approach*; it focuses on interdisciplinary knowledge and methodological approaches associated with PBL (Christensen et al., 2006).

Placement on Spectrum

In the development of the IRE model, a choice was made to select learning outcomes that reflected the outcomes from the calls for change in engineering education (see Chapter 1.3). The IRE learning outcomes focus on three interdisciplinary domains of learning: technical, design, and professional. These outcomes are communicated to students as the three domains of being an engineer. This focus places the IRE model at the *innovative and learner-centered approach* end of the objective and outcomes spectrum, Figure 4.1.

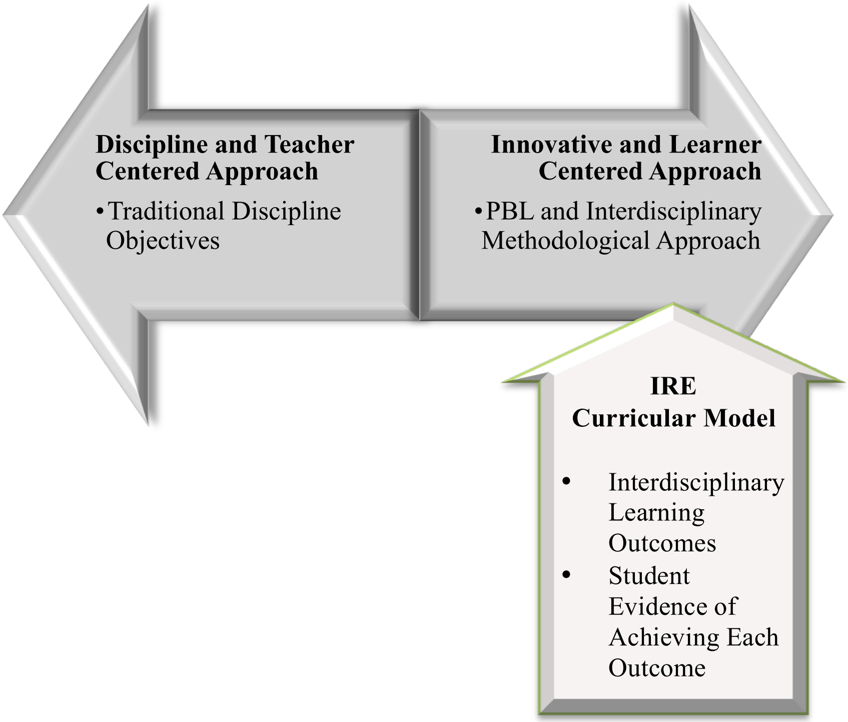


Figure 4.1. Objectives and outcomes spectrum

Characteristics of IRE Model

A program goal is to have all students achieve a desired level for each of the 14 specific learning outcomes within the three learning domains of technical, design, and professional. The IRE program is ABET-EAC accredited. As such, eleven of the outcomes are dictated by ABET. These are commonly referred to as the ABET a-k student outcomes (Abet.org, 2015). Based upon the economic development needs of the region and the recommendations of the two advisory boards, Iron Range faculty chose to add three additional outcomes: leadership/management, entrepreneurialism, and performing in inclusive environments.

Table 4.1 shows the IRE student outcomes. Appendix A includes the performance indicators (PI) that further define each outcome. It is through meeting the PIs that a student successfully meets an outcome. While ABET identifies the outcome, the individual program develops its own performance indicators. Programs achieve autonomy through the differing performance indicators.

Table 4.1. Graduate student outcomes

Technical Outcomes	**Design Outcomes**	**Professional Outcomes**
Technical 1. *An ability to apply knowledge of mathematics, science, and engineering*	Design 1. *An ability to design a system, component, or process to meet desired needs within realistic constraints*	Professional 1. *An understanding of professional and ethical responsibility*
Technical 2. *An ability to design and conduct experiments, as well as to analyze and interpret data*	Design 2. *An ability to function on multidisciplinary teams*.	Professional 2. *An ability to communicate effectively*
Technical 3. *An ability to identify, formulate, and solve engineering problems*	Design 3. *An ability to lead, manage people and projects*	Professional 3. *An ability to work successfully in a diverse environment*
Technical 4. *A recognition of the need for, and an ability to engage in life-long learning*	Design 4. *An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice*	Professional 4. *A knowledge of contemporary issue*
Technical 5. *An ability to engage in entrepreneurial activities*	Design 5. *The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context*	

The IRE outcomes and performance indicators are made explicit to each entering student as part of the orientation process. Each outcome has a rubric that describes levels of performance ranging from 1 (deficient) to 2 (weak) to 3 (acceptable) to 4 (desired) to 5 (exemplary). Table 4.2 contains an example rubric.

Table 4.2. Rubric for technical outcome 1

		Performance Levels				
Outcome Definition	**Performance Indicator**	**1 = Deficient**	**2 = Weak**	**3 = Acceptable**	**4 = Desired**	**5 = Exemplary**
An ability to apply knowledge of mathematics, science, and engineering	Verbally describe science, engineering, and mathematical concepts in an oral exam	Does not identify key concepts even with much prompting, or explanations reveal serious misconceptions	Incompletely identifies key concepts with much prompting or explains them inadequately for proper understanding	Correctly identifies key concepts with minor prompting and reasonably describes them both verbally and symbolically	Correctly identifies key concepts without prompting and explains them well both verbally and symbolically	Promptly identifies key concepts and explains them contextually with skillful use of language and symbols
	Apply science, engineering, and mathematical knowledge to solve closed-ended problems	Selects unsuitable equations or applies them incorrectly, yielding erroneous solutions to simple STEM problems	Selects and applies equations that are often unsuitable or inaccurate, produces questionable solutions to text-book-type STEM problems	Properly selects and applies equations, produces and presents correct solutions to text-book-type STEM problems	Accurately and knowledgeably selects and applies equations, correctly produces and presents accurate solutions to typical STEM problems	Skillfully selects and applies equations, adeptly produces accurate solutions, insightfully explains results to typical and novel STEM problems
	Use science, engineering, and mathematical knowledge in a deep learning activity	Does not document problem solving thought processes or documents poor thinking, problem solving, or learning achievements	Sparsely documents thought processes or documents dubious problem definition, expected outcomes, solution process, results obtained, or learning achieved	Acceptably documents reasonable thought processes for problem definition, expected outcomes, solution process, results obtained, and learning achieved	Fully documents sound thought processes for problem definition, expected outcomes, solution process, results obtained, and learning achieved	Skillfully documents exemplary thought processes for high quality problem definition, expected outcomes, solution process, results and learning achieved

The outcomes serve as the guidepost for learning. At the beginning of each semester for design and professional learning and at the beginning of each technical course, academic staff presents students with a syllabus stating course expectations. Explicit in these expectations are the learning goals for the course stated in terms of students meeting the outcomes. Students are graded in their courses using the outcomes rubrics to identify levels of performance. Throughout the two years of the PBL program, students accumulate evidence that they have met each performance indicator for each outcome. By graduation, they submit a portfolio with accumulated evidence, including a reflection where they verbalize how their work demonstrates the appropriate outcome achievement.

4.1.1. CONNECTING LEARNING OUTCOMES TO LEARNING THEORY AND RELEVANT COMPONENTS

Previously described in section 2.3 were constructivism, Illeris' model, and the American Psychological Association's (APA) learner-centered psychological principles. The relevant components of learning environments discussed were: development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity.

The graduate student outcomes describe what the student should be capable of doing at graduation, but do not describe how the student should acquire the capability to achieve the outcome. Therefore, little from the outcome statements can be directly attributed to the learning theory and learning environment components.

However, the performance indicators listed under each outcome show how students can demonstrate outcome achievement. It is in these performance indicators that relationships can be made to theory and learning environment components. The sum of the outcomes and performance indicators draw balance towards the center of

Illeris' triangle. For example (see Figure 4.2 below), in technical outcome 1, an ability to apply knowledge of mathematics, science, and engineering, the PI to "solve closed-ended problems", would be in the upper left vertex of content and cognition; whereas, the PI to "describe concepts in an oral exam" moves down the triangle as it takes place in an external interaction with others in the learning environment. Movement away from content also comes in the last PI, "use knowledge in a deep learning activity", where movement is toward the upper right vertex, providing incentive and motivation to use the learning in an application of importance to the learner. Similar balance is drawn towards the center by the PIs in most of the other outcomes.

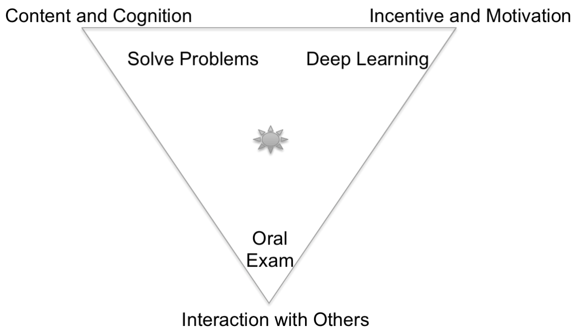


Figure 4.2. Placement of outcome on Illeris' triangle

Many of the performance indicators are constructivist in nature. To demonstrate the ability requires the student to construct her or his own knowledge; and the construction is impacted by the individual's past experiences while happening over time in a spiral type model. Example of PIs that meet this are "designing an experiment to answer a question related to technical work", "determine the reasonableness of a the solution to an open-ended problem", "critically judge design solution effectiveness based on project requirements", "evaluate quality of teamwork achieved", "apply metacognitive techniques to improve individual learning", and "write PDP goals that show interacting with others in a professional and respectful manner, in all situations, is a critical tool for success."

The 14 learner-centered goals, sequentially numbered, are listed and described in Section 2.3. Strong connections can be made between the APA learner-centered principles and IRE outcomes and PIs. Table 4.3 lists several strong connections.

Table 4.3. Connections between outcomes and APA learner-centered psychological principles

IRE Outcome	Learner-Centered Principle
Technical 1	7, 8, 9, 11
Technical 2	1, 2, 3
Technical 3	8, 9
Technical 4	2, 3, 4, 5
Technical 5	
Design 1	4
Design 2	10, 11
Design 3	12, 13, 14
Design 4	6
Design 5	6, 13
Professional 1	2, 11, 13
Professional 2	11
Professional 3	10, 13
Professional 4	11

The learning environment components directly addressed by the outcomes are the following: *reflection and metacognition* as they are required by the PIs in technical outcome 4 requiring learning journal reflections and use of metacognition; *motivation* as it is built by the contextuality of the design outcomes; *situativity* and learning community in design outcome 3, regarding team interactions; and *identity* as it is built in the elaboration of the professional development plans in professional outcome 1.

The learning outcomes of the IRE model are directly supported by the other curricular elements. Of greatest significance, is the type of project and how the design process and learning experiences support the student development of the learning outcomes, as demonstrated by their growth in the performance indicators.

4.2. TYPES OF PROBLEMS, PROJECTS, AND LECTURES

The heart of any project-learning program is the projects and how they interact with the lecture part of the student learning experience. For the curricular element of types of problems, projects, and lectures, there are closed-ended problems at the *discipline and teacher-controlled approach* end of the spectrum, which are identified with the traditional specific steps to a solution and a specific answer. At the i*nnovative and learner-centered* end of the spectrum*,* projects are ill-defined which leaves both the approach and the final solution to be determined by the teams and the students. These types of projects support the interdisciplinary approach of PBL.

Lecturing is part of the whole spectrum for this curricular element; however, its focus, content, and duration adjust based upon the type of problem and project work students are doing. In the *discipline and teacher-controlled approach,* lectures focus on knowledge transfer from the expert to the student. In the *innovative and learner-centered approach,* the lectures support the project. The emphasis shifts from knowledge-transfer to guiding students through the knowledge acquisition process as directed by their project work.

<u>Placement on Spectrum</u>

The development of the IRE model is characterized by the use of industry-sponsored projects with well-defined project scopes and open-ended solutions. The learning activities, or the “lecture component”, of the curriculum are a purposefully integrated part of the project work and learning experience for the students. See Figure 4.3. This places the IRE model towards the *innovative and learner-centered approach* end of the objective and outcomes spectrum.

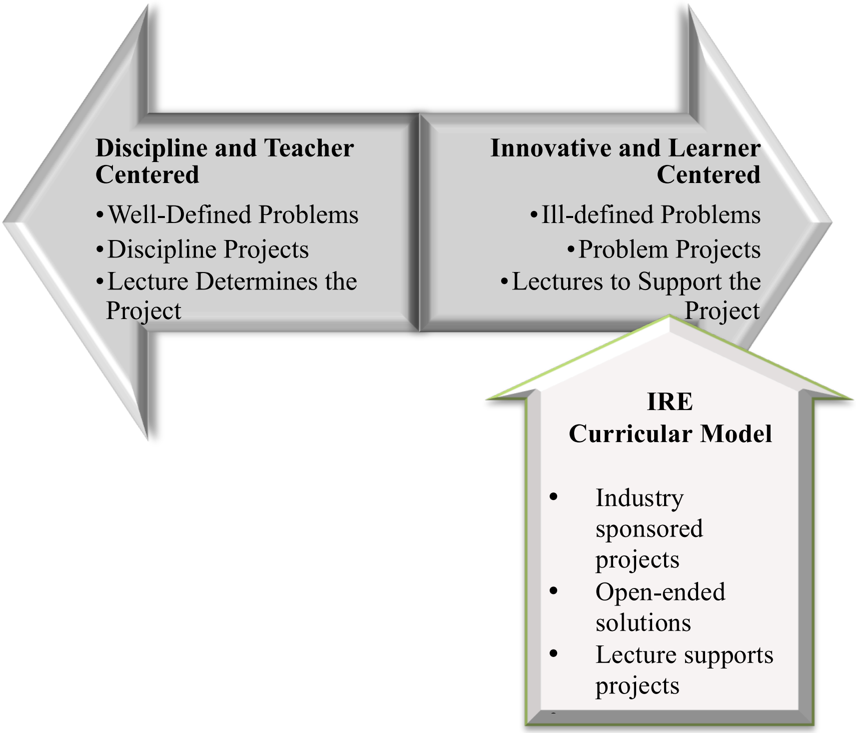


Figure 4.3. Types of problems, projects, and lectures spectrum

<u>Characteristics of IRE Model</u>

The project cycle in the IRE program lasts one academic semester. During the semester, one team, with the guidance of a project facilitator, completes a project for a client. The client is normally an industry partner; however, students can choose to do an entrepreneurial project in which they are their own client, inventing their own product or process. The industrial projects are real needs the company has for engineering solutions. The intent is for the companies to implement the student solutions. This often happens.

The process starts prior to the semester when students are queried about their interests in project types for the upcoming semester. Potential interest areas include, but are not limited to these: industrial mining, industrial other, manufacturing, consulting, biomedical, or entrepreneurial. Based on the results of this survey, the academic staff sends out a call for proposals to the program's current and potential industrial partners. See Appendix B for a sample project solicitation form. Students interested in an entrepreneurial project complete the same form. Once the industry partners and entrepreneurial students have submitted complete solicitation forms, the forms are compiled into one document that is deemed the "projects menu." The projects menu is distributed to all students. Students then select their top three choices. Academic staff compiles all of the student desires and create teams. Other considerations that staff use when assembling teams include prior student experiences and student personalities. The intent is to create a vertically integrated team with students from different semesters of the program and with different skill sets and development needs. Once a team has been assigned to a project, a project facilitator from the academic staff is selected for the team. Prior to the first day of the semester, the project facilitator will have met with the client to get a clearer understanding of the project scope.

The projects serve as the backbone for the student learning of the design, technical, and professional outcomes. The projects are selected to support the student competency development process such that they are able to demonstrate all 14 competencies by the time of graduation. The development of the student design outcomes will be described in the next Section. The technical and professional outcome development will be described in Section 4.4, students' learning curricular element.

4.3. PROGRESSION, SIZE, AND DURATION

A defining characteristic of the progression of PBL is the percentage of time committed to project work or the extent of the project work within the curriculum. It is relegated to a minor part in the *discipline and teacher-controlled approach.* It could be an add-on to one or more courses or serve as a capstone senior design project.

In the *innovative and learner-centered approach*, the projects consume more and more time within the curriculum. As the time dedicated to projects increases, so does the impact the project work has on student learning. The learning outcomes that can be achieved in the PBL curriculum are dependent on this time commitment, as the learning takes time within the project teamwork.

Placement on Spectrum

In the development of the IRE program, a choice was made to focus on the 14 outcomes and for the students to develop depth in knowledge of each. This is in contrast to the breadth of discipline-specific topics pursued by most traditional programs. Within this PBL process, students are trained and developed in their ability to be self-directed learners. The intent is that students are deeper design, technical, and professional learners who have the ability to learn additional competencies in these three domains to support their careers in industry. This characterizes the IRE model as *innovative and learner-centered* as shown in Figure 4.4.

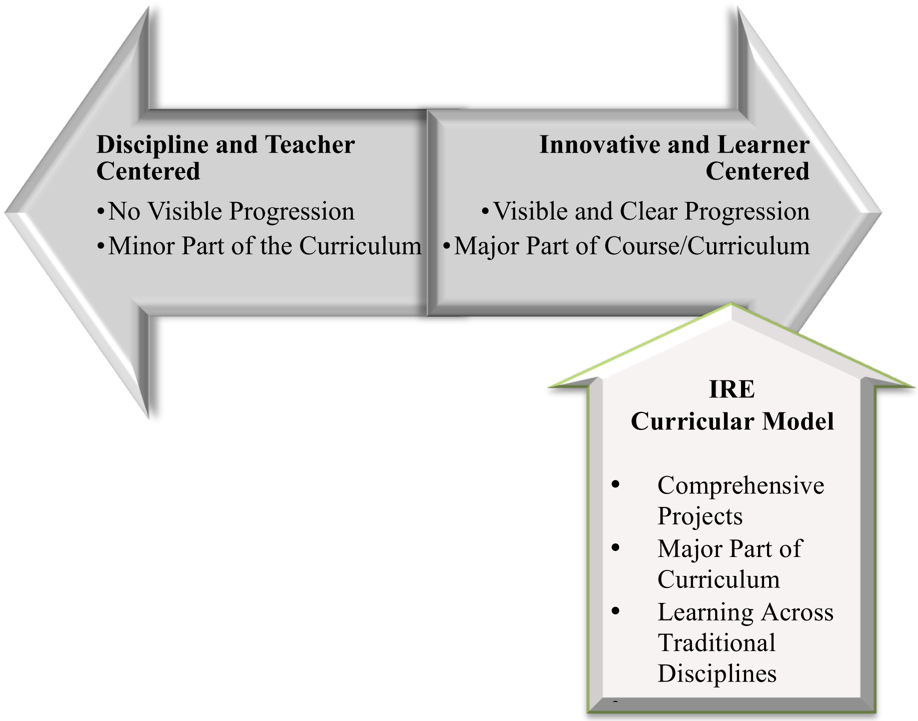


Figure 4.4. Progression, size, and duration spectrum

<u>Characteristics of IRE Model</u>

From the Savin-Baden models of PBL (2000, 2007) (from Section 2.5), the IRE program includes the following:

- the student learning organized around problems/projects;
- the project as the incentive for the student learning process and is a central principle to enhancing student motivation;
- the projects that are concrete ones that students are attracted to on the basis of their own experiences and interests; and
- the project reflects the conditions of professional practice.

In connection to the Savin-Baden models of PBL, the IRE program has elements from the Model III, *PBL for Interdisciplinary Understanding* with some aspects of Model IV, *PBL for Critical Contestability.*

The focus of the design process is to develop students in all three domains. The description of the design process will focus on student development in the design domain. The IRE design process and its components are depicted in the Figure 4.5 graphic. The model is borrowed from Litzinger (2015). Students often picture the process as the floor plan for a circular house with each area being a virtual room in the home. The first room entered is problem definition.

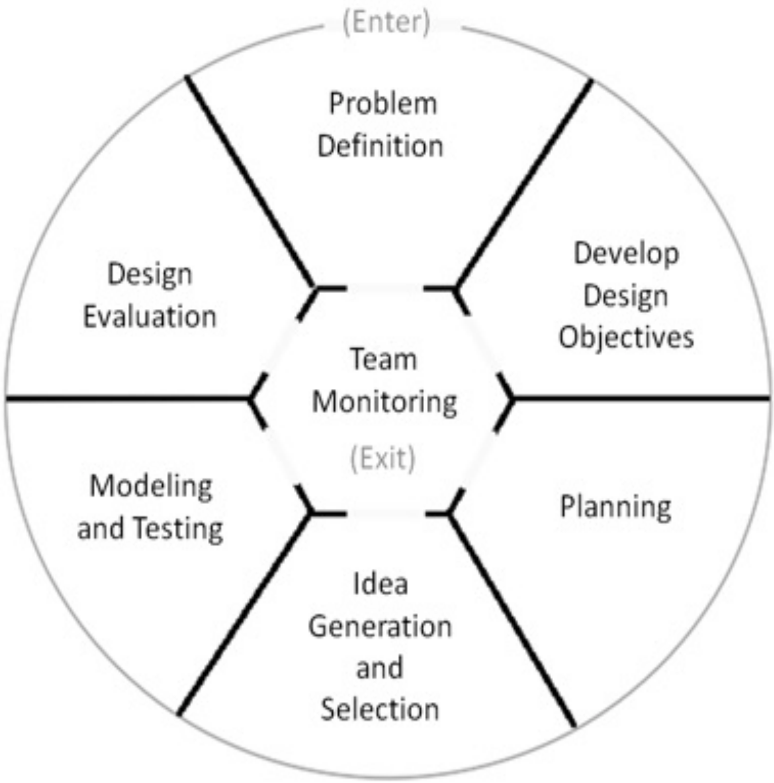


Figure 4.5. IRE Design Process

4.3.1. PROBLEM DEFINITION

Students use the project solicitation form supplied by their client to establish a draft of problem definition. With this draft definition in hand, they travel to the industry site for an initial scoping meeting with the client. At this meeting, they further identify the driving forces behind the design, trying to determine what changes in the client's environment propel the new need. Such factors could include new technical opportunities, changes in regulations, changing economic factors, etc. Further, the team identifies the requirements and constraints. From the requirements, students are able to understand the necessary components to be included in the final design deliverable for success to be achieved. These requirements should be concise, measurable, and quantified. Constraints are the limiting factors as identified by the client and usually include costs, size, user inputs, standards, regulations, etc. Upon returning from the initial client meeting, the students update their draft problem statement to a final problem statement and then submit it back to the client for approval.

As the students leave the problem definition room from Figure 4.5, they enter the team monitoring room. Each time the group enters this virtual room they ask questions, the answers to which will determine which room they should enter next. A typical question at this juncture might be "is the scope of the problem definition appropriate, considering the time resource available to us?". If the answer to this question is yes, the students would likely move into the "develop design objectives" room. If the answer is no, they will move back into problem definition and, in conjunction with the client, refine the problem definition.

4.3.2. DEVELOP DESIGN OBJECTIVES

The first step in this stage is to identify the needs of the end user. Students will look to interview or survey an appropriate sample of the potential end users of the design. By identifying these needs and quantifying the relative importance of the needs, the students bring an essential component into the design objectives. Using the end user needs and requirements and constraints from the problem definition stage, the team can create a set of goals that, when met, will result in a final design for the client. These goals are referred to as the design objectives. The design objectives should be concise, quantitative, and forward-looking. Design objectives are submitted to the client for feedback to ensure that the team direction aligns with the client desires.

When leaving the design objectives room, students return to team monitoring. Here they compare their design objectives with the problem statement to ensure compatibility. They again check for appropriateness in regard to resources available for completion of the project. Answers here can lead to problem definition refinement, design objective refinement, or advancement to the planning stage. Table 4.4 shows sample design objectives.

Table 4.4. Sample project team design objectives (used with permission from Hanegmon, Benes, and Schumacher)

Objective	Method of Measurement	Target
Safety	Operator can safely utilize system	No operators in confined spaces
Ability to drain system	The system will properly pump the water out of the condenser pits	System will drain the condenser pits as low as top of strainer
Compatibility with Other Systems	The system's performance based on all associated systems as well as other system's performance based on condenser pit's pumping system	The system will be designed to function in accordance with all associated systems
Maintainability	Amount of time and maintenance required once installed	Design for low-cost, time, and effort towards maintenance
Withstands corrosion	Visual inspection after regular use	Withstands regular corrosion
Create supporting documentation	Operating procedure, timeline, updated P&IDs and final document to client will be created	Operating procedure, timeline, updated P&IDs and final document to client will be created
Reliable performance	Operation time without major repairs	System will be designed to an acceptable lifespan according to manufacturer's specifications.

4.3.3. PLANNING

Upon approval of the design objectives by the client, the team develops a detailed project plan. The project is broken into well-defined tasks. Each task has an estimated completion time, person(s) responsible, and start and end dates. The team creates visual representations of the plan in the forms of Gantt charts or Microsoft Project charts. The plan is printed and displayed in the team room for quick reference. The project plan is a dynamic document. Team members continually track project execution as compared to initial timelines. The plan is frequently updated as new tasks arise, old tasks are completed or deleted, and the project continues towards completion.

When the team leaves the virtual planning room for the first time and enters the team monitoring room, they evaluate the completeness of the plan in regard to the problem definition and the design objectives. Throughout the execution of the rest of the project, the team will return many times to the project planning room to make the updates and track the progress.

4.3.4. IDEA GENERATION AND SELECTION

Central to the act of design is the development of creative solutions to the design problem. It is when entering the virtual "idea generation and selection room" that the team ideates potential solutions to meet the client's needs while operating within the constraints imposed. The key to the idea generation process is extensive research on past works of others and the identification of the engineering fundamentals that dictate the science under which solutions can be developed. Team members work individually or in small sub-teams during initial idea development. As time goes by, the larger team comes together to synthesize ideas and create hybrid ideas.

Following initial idea generation, the team goes through a selection process such as the Pugh matrix method (Pugh, 1991) where they assign weights and values to aspects of each idea, creating a scoring system that allows an aspect of quantification to the selection process. As one or two ideas rise to the top, another round of idea generation begins in which further hybridization can result in improved designs. At several junctures during the idea generation and selection phase, the team retreats to the virtual team monitoring room. There they can evaluate ideas, as compared to design objectives and the design problem statement, and also return to the team planning room to make necessary adjustments to the team plan. See Table 4.5 for an example design decision matrix.

When the team ultimately settles on one or two designs that can be brought forward in the design process, they enter the modeling and testing phase.

Table 4.5. Sample project team design decision matrix (Hanegmon, Levar, Nelson, Syzmonowicz)

Concrete Test Procedures								
Brand	Hot Tire	Wear Marks	Oil Test	Slipperiness		Hot Works	Drop Test	Total
Drylok 1part epoxy	2	2	5	3	5	3	3	23
Painters Select premium porch and floor	2	1	5	7	8	4	5	32
Drylok Concrete Floor Paint	4	2	5	0.5	1	2	5	19.5
Rustoleum	1	2	5	3	4	1	5	21
Porch & Floor	0	8	5	3	4	1	5	26

4.3.5. MODELING AND TESTING

When initial designs are selected, the team creates a method to test the designs as to their ability to meet design objectives. Often this testing includes the creation of prototype models and the design of experiments. Students start with a specific plan for modeling/testing where they carefully lay out the purpose of the test and the step-by-step procedures they will follow. The modeling can include physical, non-working models that are used to further ideate aspects of the solution. Such models are made on 3-D printers, laser cutters, or out of foam or balsa wood. More advanced models achieve the prototype level and are working models made out of the materials that are more likely to be used in the actual implementation. Students design and conduct experiments, using the models to demonstrate the ability of the designs to meet initial objectives and constraints. There are many failures of the designs during this stage. Design failures result in a return to the idea generation and selection phase in which design improvements are ideated, then back to modeling and testing for the implementation of the design improvements.

As during the initial idea generation selection/phase, there are several times during modeling and testing when the team returns to team monitoring to check schedule and alignment with design objectives, constraints, and problem definition. Figure 4.6 is an example project team test plan.

Test Plan

General: This document will contain the main design goals that the team would like to meet for the 2015 Mini Baja. It will describe the design objective, the purpose for each goal, and the procedure of how it will be tested.

Weld Test

Purpose of Test: The purpose of the weld test is to test the strength of the welded joints in relationship to the material. According to SAE Baja rules the strength of the welds must be greater than the strength of the material, and therefore must fail before the welded joint when put under load. This test is also to check if the weld is reaching full penetration in the material.

Test Objective: Test the strength of the welded joint by applying a force to the test piece until failure and observing if the failure point is in the material or the welded joint. We will also cut a welded sample and analyze the depth of the weld penetration to assure it is going all the way through the material.

Test Procedure:

1. Cut metal to appropriate length.
2. Perform coping cuts on one end of the metal.
3. Weld the metal in a "T" shape.
4. Put sample piece into the test fixture.
5. Apply force on piece with floor jack until failure as shown in *Figure 1*.

Figure 4.6. Sample test plan

4.3.6. DESIGN EVALUATION

As the team nears completion of the design project, they begin formal evaluations of the design results. Based on the inputs from the modeling and testing phases, they evaluate the final design against all design objectives and constraints. They identify strengths and weaknesses of the design as compared to each objective.

From this analysis, students develop a set of design improvements. If time allows, they begin making some of the design improvements. If not, they create a design improvements document that is submitted to the client, along with the final design documentation.

4.3.7. PROJECT COMMUNICATION

Throughout the design cycle, the team is responsible for several forms of communication. These include written documentation, formal presentations, poster creation, informal design reviews, and client interactions. Required written documents include the following: team contract, design problem summary, design concepts document, design selection document, testing plan, and final design evaluation. Formal presentations include these: scoping presentation (after initial planning phase), technical presentation (at mid-semester, detailing the deep use of engineering principles in the design), final design review (formal team exam at the end of the semester, and final client presentation. Informal presentations include the following: weekly design review with project facilitator and periodic client update presentations. Upon completion of the design objectives stage, the team creates a 24” by 36” poster describing their project for public display in the program passageways. Figure 4.7 shows an example of student team project poster.

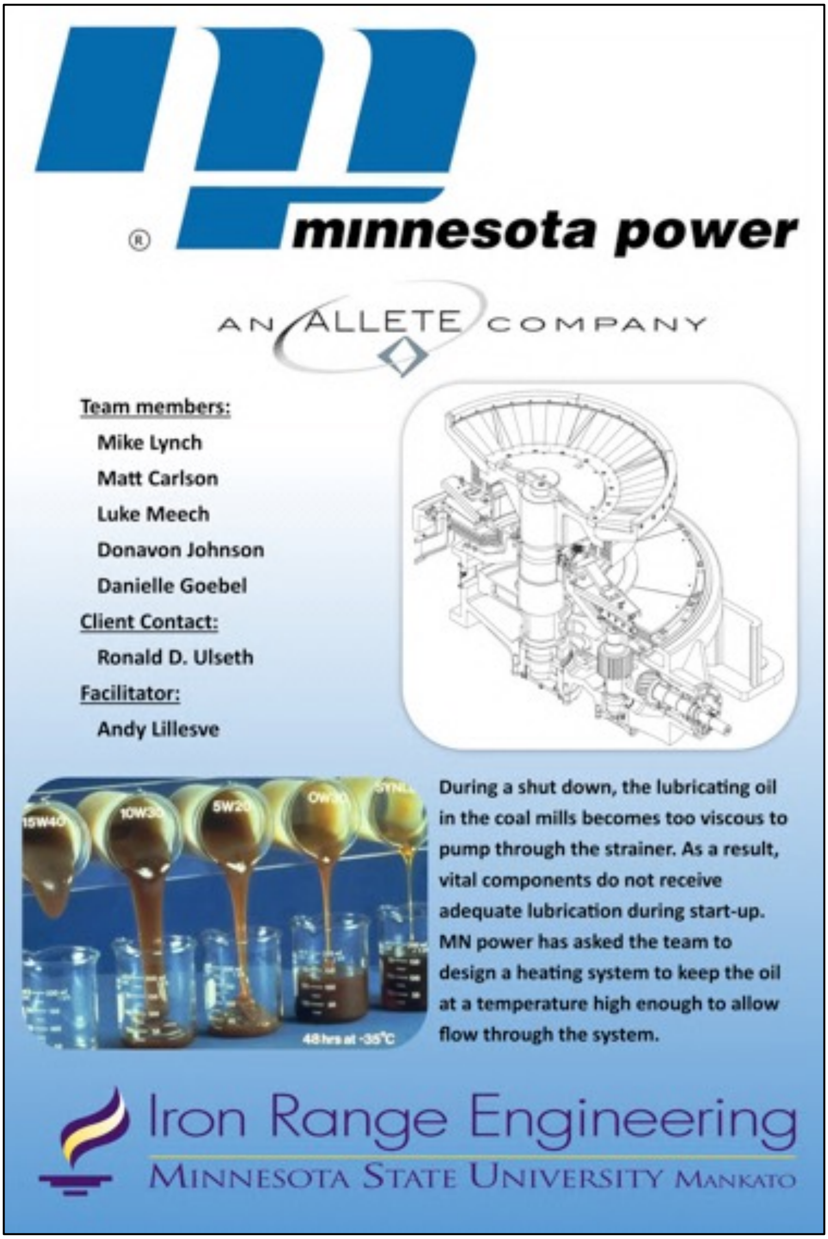


Figure 4.7. Sample project team poster

4.3.8. PROJECT FACILITATION

A member of the Iron Range Engineering academic staff acts as a project facilitator for each team. Usually, there is one team per faculty member. The backgrounds of the facilitators range from PhD academicians to late-career practicing professional engineers, to recent BS engineering graduates of the IRE program. All of these facilitators bring different, valuable perspectives to the academic staff.

The project facilitators serve the team in a variety of functions. They serve as the liaison between the team and the industry client. The purpose of this role is to have a clear understanding of the needs of the client so that when the student groups have a misperception of client needs, the facilitator can guide to a redirection. Their role is not to serve as a middle-person between the client and the team. It is important that the team members maintain full and open communication with the client. So in this respect, the liaison has to definitely work from the side, encouraging the students to act, rather than acting on their behalf. From the client perspective, it is important for the facilitator to manage expectations. Most clients don't know what to expect from the IRE teams. Some expect a level of work far higher than that of which the teams are capable and some expect far lower. The facilitator can communicate with the clients to help them have expectations at which levels the students will deliver. This leads to higher levels of client satisfaction upon project completion. The facilitators clearly set the expectation that project is a learning experience for students, as well as being an asset for the client.

The project facilitator performs the role of design instructor. Students do not enter the program with a full understanding of the design process nor project management, nor how to create innovative solutions. Through a coaching environment, the facilitator guides the students toward advancement in their understandings of the processes and their abilities to execute. The facilitators take a scaffolded approach, providing more structured guidance to new students, removing the structure as the students move through the four-semester program, to a point at which graduating seniors are expected to act with little supervision.

Each week, the facilitator meets with the team for several hours. During these periods, students present informal design reviews, describing and defending their actions and progress from the previous week, current project status, and plans for the upcoming week. Additionally, during this weekly meeting, the facilitator guides student discussions on ethics, contemporary issues, and helps each student track his or her progress on the learning goals. A major focus is the student development of the professional competencies and helping to guide individuals and the team through the development process.

All program facilitators meet for one hour per week to share experiences, discuss the progress of their teams, and provide peer learning and feedback.

4.3.9. TEAM COMPOSITION

The program has experimented with team makeups. This is regarding who selects the team makeup, the academic staff or the students themselves. It is also in regard to the student levels, teams made up of all students from the same level or vertically integrated with new students through graduating seniors. At the time this thesis is being written, the program has settled on vertically integrated teams selected by the students themselves. The advantages of being vertically integrated include experienced students being able to guide newer students through team and design processes. The advantage of student selection of teams comes from students gaining a higher level of ownership in their own educational decisions.

4.3.10. LEARNING THEORY AND RELEVANT ELEMENTS – DESIGN LEARNING

The design learning, as described above, draws from all corners of Illeris' triangle. In the upper left, the content includes the acquisition and practicing of the design process, as well as the technical attributes of the design. In the upper right, motivation is drawn from the real-world importance of meeting a client's need on a project and on a team that the student selected himself. Moving down Illeris' triangle brings into account the interactions within the team and external to the team, as well as how the design interacts with its users. Many arguments can be made about the IRE design experience having attributes in each corner, thus enabling a placement of this process near the center of Illeris' triangle.

The constructivist aspect of the design learning comes from the inter-relatedness between the technical competence students have acquired previously or during the design process. Substantial new knowledge is constructed as students advance their learning of a fundamental principle at the conceptual level to real use in the execution of design. The knowledge constructed at this level is then available for use, and further development, in another cycle of the learning spiral in future projects.

Most of the APA principles come into play in the IRE design learning process. The cognitive and metacognitive factors that are applicable include the nature of the learning process, the goals of the learning process, the construction of knowledge, and the context of learning. The motivational and affective factors are all high, due to the ownership students have in choosing the team and project, and the contextuality due to the perceived importance of the real projects. The team and learning community environments established during the project influence development and social factors.

Important factors in the development of expertise include heavy emphasis on reflection, inquiry, and students inventing and developing instruments to work more efficiently. The design cycle, traversed four times by each student, takes place in an environment where facilitators scaffold these factors, specifically during weekly design reviews.

Scaffolding is present in the design-learning as new entering students are given much guidance on all aspects of design. Then, slowly, that structure is removed until the students are in their last semester and have the freedom and responsibility to do the process with very little guidance, and are even expected to provide some of the guidance and structure to the most junior members of their teams.

Motivation on design teams and projects is high, due to many factors: student ownership in decision making, contextuality provided to all other learning domains, reality the of use of their products by clients, and the high expectations of the clients.

The design learning experience highly influences the situativity of their learning. The environment of the project room, fabricating labs, and industry site, the artifacts and communities of which they are a part, and the actions of professional practice all cause the learning to be distributed among the learners and everything around them.

The design team, their facilitator, and their clients form a unique learning community. The members share many of the same learning goals, activities, physical spaces, and spend much time together. These communities build anew, each semester, and are centered on the design project. Students are given special instruction on how to develop stronger teams through activities and respectful actions. Their success in building strong communities impacts their design success and overall learning.

The act of performing engineering design on a team for a real client and creating tangible products and systems that will be used by the client, all while doing so in an environment that has been designed to simulate professional practice, creates the opportunity for members of the team to develop higher levels of identity. The level to which the identity increases is dependent on the mindset of the individual and her peers, as well as the facilitator and the client.

As the discussions on the team projects progresses and the IRE design process transitions into focusing on the student learning in Section 4.4, it is important to emphasize the importance of the project facilitator. The academic staff not only oversee the project itself and facilitate student learning of the design domain outcomes, but they are an integral part of students connecting their technical and professional domain-learning to their project work. As students generally enter an engineering curriculum with little to no experience or training in functioning as a team, or how to manage projects, it is important to have someone to guide them through this process.

4.4. STUDENTS' LEARNING

In the traditional *discipline and teacher-controlled approach,* student learning is focused on knowledge acquisition; and the motivation for any collaborative learning is for each individual's learning. Students entering these types of programs are typically not provided with instruction on "how to learn."

In contrast, the *innovative and learner-centered approach* is characterized by the student-learning being more about the construction of knowledge and understanding, with the collaboration between students being focused on creating knowledge with others for the benefit of all. In a PBL curriculum, a student-learning structure exists to support the students acquiring the program learning outcomes. Students typically enter the program with experience learning as individuals, with little experience learning in a team and learner-centered environment. Critical to student success, in a PBL model, is the incorporation of support courses that develop student attitudes and expectations towards the PBL model of education while also developing their abilities to learn in the collaborative learning environment.

Placement on Spectrum

In the development of the IRE model, a choice was made to focus on creating learning experiences and activities that develop students' knowledge in the technical and professional domain that directly support the project work. The intent is that the collaborative learning within the project teams is focused on constructing knowledge for both the completion of the project and for the team members to achieve the program learning outcomes, which they are focused on for that given semester. With this focus, the IRE model lies at the *innovative and learner-centered approach* end of the spectrum as shown in Figure 4.8.

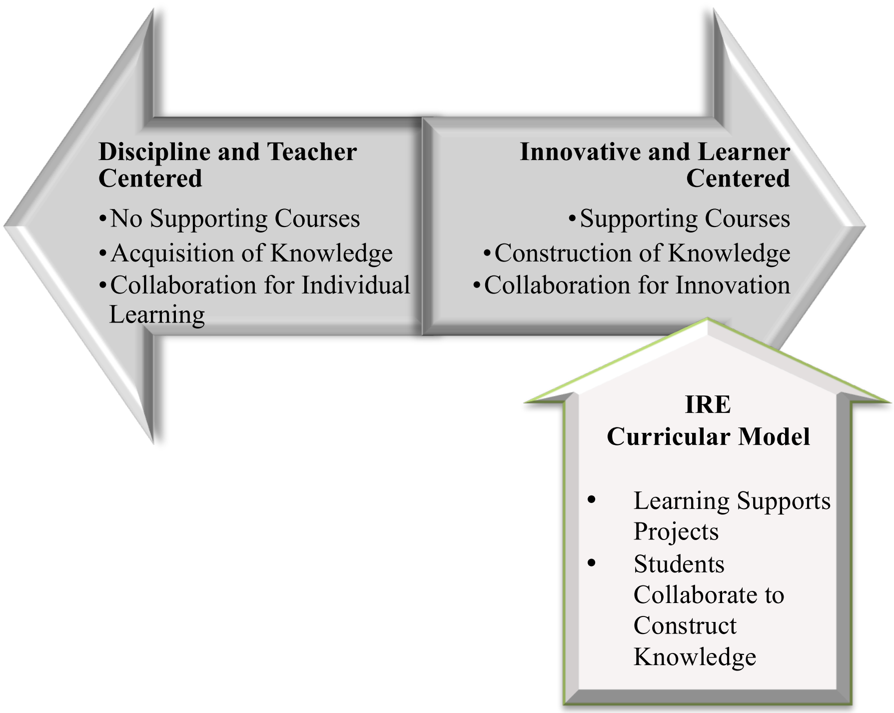


Figure 4.8. Types of students' learning spectrum

Characteristics of IRE Model

This section will specifically look at the IRE model approach to students achieving the technical and professional learning outcomes. It will close with the role of the IRE social culture on student learning in all three domains.

4.4.1. TECHNICAL CURRICULUM

Technical learning makes up 32 out of the 60 semester credits in the IRE two-year program. Students average 8 technical credits per semester. Each credit is a stand-alone course, referred to by IRE students and instructors as a "technical competency." Of the 32 competencies, 16 are deemed as "core" (required by every student) and 16 as "advanced" electives. Core courses include thermodynamics, material science, fluid mechanics, manufacturing processes, dynamic systems, mechanics of materials, instrumentation, electronics, electric machines, digital logic, AC, controls, entrepreneurialism, engineering economics, statistics, and programming/modeling. It is through the makeup of the advanced competencies that a student can choose depth, to focus on a particular area of engineering, or choose breadth to become more of a generalist. All students earn a Bachelor's of Science degree in Engineering (BSE). Students who take 14 out of 16 credits in a depth area can earn an "emphasis" in that area. The emphasis comes in the form of a department letter describing what their emphasis is and what competencies and projects they completed. Emphases have been awarded in mechanical engineering, electrical engineering, biomedical engineering, chemical engineering, and engineering management.

4.4.2. TECHNICAL COMPETENCY SELECTION

Students have control over which competencies they take each semester. They receive guidance from the program director during seminar, and individual guidance from both their advisor (an academic faculty member they are assigned to for their four semesters) and their project facilitator (an academic faculty member who guides their project during a given semester). As students decide which competencies they will pursue each semester, they have two objectives they are trying to meet. The objectives are choosing learning that benefits their semester project and choosing learning that is aligned with their desired depth emphasis area. Most often there is overlap between these objectives. Most student projects align with their desired depth emphasis. The courses are delivered in two half-semester periods called "blocks." At the beginning of the semester, students decide which four competencies to take for the first block. Then, at mid-semester, they select four competencies for the second block. The goals of this system are to provide flexibility and student ownership. By choosing which competencies to take when it makes the most sense for the project, the students have the opportunity to have high levels of contextual relevance. Again, it is mentioned that academic staff are available to provide guidance when students are unsure of what is the most appropriate set of competencies to pursue.

4.4.3. TECHNICAL LEARNING PROCESS

The first day of each competency is called "syllabus signing day." To this conversation, the students and the instructor bring their hopes and expectations for the course. Together, they discuss these expectations and design the layout of the course in terms of learning activities, deliverables, and evaluation. Figure 4.9 details the expectations of a day one conversation.

Day 1 Learning Conversation Expectations:

- Faculty member brings electronic copy of updated syllabus
- Discussion of:
    - pre-requisite knowledge
    - student learning goals
    - faculty learning goals
    - DLA expectations and plans
- Daily expectations for students and faculty
- Rough draft of timeline
- Day 1 homework assignment
- Print and sign syllabus

Figure 4.9. Day 1 learning expectations

A typical competency has 10-15 students and one instructor. The instructor and the students will meet 2-3 hours per week for 6-7 weeks in “Learning Conversations” (LC). A learning conversation is a time during which students and instructors can make conceptual sense of the learning. This is done in flipped-classroom type of method in which students do initial learning between LCs and then use the time together in LCs to ask questions and discuss the relevance of the learning. The three required learning types in any competency are conceptual, process, and metacognitive.

Conceptual learning is focused on connecting all learning to the fundamental principles of engineering. For example, if students were taking a competency in heat transfer, they would learn the concepts of conduction, convection, and radiation. Then they would connect these concepts to broader engineering fundamentals such as the law of conservation of energy and the 2^{nd} law of thermodynamics. Learning activities in conceptual learning include reading, watching on-line videos, working problem sets, creating concept maps, and discussion.

In *process learning,* students connect their conceptual learning to engineering practice. They do this by completing a Deep Learning Activity (DLA). Whenever possible, the DLA is work done in the design project such as design, testing, or modeling. For some examples, we can return to the learning of heat transfer. It is not unusual for IRE project teams to be designing heat exchangers for their clients. The act of completing that design would be a DLA for a heat transfer competency. Another example, if heat exchanger design were not required, would be for the students to design and conduct an experiment verifying heat transfer, using physical equipment and instrumentation. As the domain of learning spreads across all of engineering, similar type process learning opportunities are found in abundance.

During learning conversations, instructors help students make connections between their conceptual learning and their DLA, as well as provide technical assistance to students during their DLA.

Metacognitive learning happens through students planning their learning, organizing and reorganizing their factual and conceptual knowledge, reflection, evaluation of their learning, and using the reflections and evaluation to dictate future learning. Each student keeps a learning journal for every competency, in which they record this planning and organization and write the reflections and judgments. At the end of each block, students write a metacognitive memo analyzing their learning during the four competencies, and making future learning goals. Appendix C details the metacognitive learning process at Iron Range Engineering.

4.4.4. LEARNING THEORY AND RELEVANT COMPONENTS – TECHNICAL LEARNING

Certainly, technical learning is about content. However, the action of acquiring and then using that knowledge is greatly impacted by incentive and interaction. These three make up the corners of Illeris' triangle, with content in the upper left, incentive in the upper right, and interaction at the bottom. The content in the technical learning is focused on the conceptual understanding of the fundamental principles of the discipline. The act of learning, for most students, requires incentive, an understanding of why they want to learn the material, a motivation for the action. At IRE, the incentive for technical learning comes from one of two major areas. The incentive is either to acquire the knowledge so that it can be used in the design or to acquire the knowledge as part of reaching their desired competence in the chosen area of technical depth. In the IRE model of technical learning, interaction happens in small groups of students and instructors who are working together to first acquire the competence, and then to use it in the DLA. This interaction is between the learner and his environment and between the learner and her peers/instructors. This distribution of actions within the IRE technical learning process argues for learning to be near the center of Illeris' triangle.

IRE technical learning is constructivist in nature. Rather than delivering the conceptual information to the students in a lecture, instructors guide students to build conceptual models by using motivation, conversation, and application. Students perform daily reflection and organization in their learning journals. The goal, by the time of the oral exam, is for the students to have created a technically accurate conceptual model that they can first describe to themselves and then verbalize to their instructor. The deep learning activity allows the student to experiment with using the knowledge in a, usually physical, process in which they can observe interactions and draw conclusions.

Nearly all 14 of the APA principles are in play in the IRE technical learning model. Starting with principle 1 in which learning is "an intentional process of constructing meaning from information and experience" through setting learning goals, strategic thinking, thinking about thinking, and contextual influences. Instructors set up a learning environment with many opportunities for high levels of motivation, including creating novel and challenging tasks relevant to personal interest, while providing for personal choices and control. Further, the learning has many social influences through interactions with peers and instructors. The IRE model adapts to the individual differences in learning and accounts for differences in cultural and social backgrounds. Finally, the technical learning is done with regard to high and challenging standards, while providing substantial feedback during the learning process.

Developing expertise is a goal of the technical learning model. The attributes of learning that lend to expertise development are thinking about thinking, focusing on the fundamental principles, and doing so through inquiry.

Formal reflection is an everyday part of IRE student technical learning. This is done in an attempt to develop graduates capable of reflecting-in-practice; so they can descend into the complex, ill-structured problems associated with Schön's swamp, as described in Section 2.4. Further, through the IRE metacognitive process, students spend time thinking how they learn, how well they learn, and how they can learn better. Reflection and metacognition are explicitly developed attributes in students during their technical learning.

During the learning conversation process, the instructor treats the students like apprentices learning a trade. Using scaffolded guidance, questioning, and answering, instructors promote the students' active participation in the development and achievement of their learning goals.

Situativity distributes knowledge "among people, their environments, objects, tools, books, and communities" (Greeno et al., 1996). In the IRE technical learning environments, the community, the physical space, and the objects of learning are emphasized and designed for effective learning. Students are continually placing their daily learning with representations, aligning with professional practice, and using their learning in design. This situativity leads to the building of identity, through alignment, with the people and actions of professional practice. Identity is further emphasized by approaching technical learning in a self-directed manner, just as engineers in practice are expected to do, on a daily basis.

4.4.5. PROFESSIONAL CURRICULUM

Professional learning activities include ethical discussions, performing outreach, leaderships, communicating in writing, verbally and graphically, learning to succeed in a diverse environment, becoming aware of contemporary issues, developing a personal marketing plan, practicing career searches, and meeting the professional competency expectations of an IRE student. Almost all of the professional learning takes place in conjunction with the activities of the design project. Ethical discussions take place in context with the engineering work being done on the project. Writing, presenting, and making graphical representations are executed for the written, presentation, and poster requirements for the design project. Contemporary-issues-learning has an engineering and technology slant. Design teams can include relevant contextual aspects, such as economics, sustainability, environment, social, and political aspects in their design solutions. The daily interactions between students, and between students and academic staff, are expected to take place at high levels of professionalism. See Figure 4.10 for the professional expectations of an IRE student.

Professional Expectations of IRE Students and Staff

As members of the IRE community, we are expected to act professionally with one another and with people external to the program.

Below is a list of important professional behaviors that an IRE student should follow.

When anyone in the program is acting unprofessionally it is important that he/she is informed—this is the responsibility of everyone, and should be done in private.

1. Pay close attention to our emails – acknowledge their receipt, act on requests.
2. When told something, write it down and ask questions for clarification.
3. Arrive at all class periods on time – being respectful of time.
4. Dress and groom appropriately.
5. Treat all others with respect.
6. Maintain a positive attitude.
7. Do not take frustrations out on those around us.
8. Work hard to create an environment free of harassment.
9. Willingly help others inside and outside of IRE.
10. Speak professionally, free of vulgarities, and with appropriate grammar.
11. Meet all deadlines.
12. Meet the needs of our teams by completing work on time and of high-quality.

13. Give proactive feedback to others.
14. Be willing to accept and give constructive criticism.
15. Keep IRE clean – Both personal and common spaces.

Figure 4.10. Professional expectations of IRE students and staff

Professional learning is seen as a continuous process from entry into the program until graduation. During the first semester, students begin the creation of their own Professional Development Plan (PDP). The PDP has eight sections:

- Functioning on a team
- Communicating in writing
- Presenting
- Acting ethically
- Being professionally responsible
- Leading
- Learning about learning
- Being Inclusive

In each section, the students evaluate their current level of performance, providing evidence of their judgment, set goals for improvement for the next semester, and write an action plan for achieving the goals. Table 4.6 shows the scale students use for these self-analyzes.

Table 4.6. Professional development plan self-assessment scale

Performance Levels				
1 = Deficient	**2 = Weak**	**3 = Acceptable**	**4 = Desired**	**5 = Exemplary**
Shows little evidence of desired performance, clearly not acceptable for IRE graduates	Shows some but inadequate evidence of desired performance needed in IRE graduates	Shows moderate evidence of desired performance, minimally acceptable for IRE graduates	Shows strong evidence of desired performance, clearly meeting high expectations of IRE graduates	Shows unusually strong evidence of performance as a skilled professional, exceeding expectations of IRE graduates

Every semester there are several learning activities that empower students to achieve growth in each of these competency areas. These learning activities include the following: workshops by external experts, workshops by IRE academic staff, peer discussions, assigned readings, student presentations, videos, and personal reflection. In addition to learning opportunities, there are multiple methods for feedback on development. Examples include daily informal feedback from faculty to students, formal peer reviews, formal personnel evaluations from project facilitator to each team member at the end of the semester, and grading of various professional documentation submittals. The PDP is a comprehensive document; wherein, each semester the student adds her or his new assessments, goal, and action plans, allowing for visible changes in development throughout the education. See Table 4.7 for an example section from an IRE student's PDP.

Table 4.7. Sample chapter from an IRE Student PDP (used with permission, Olafson)

<table>
<tr><td rowspan="3">Function on a Team</td><td>Current Evaluation</td><td>For this expectation of an IRE student, I would place myself as a 4 on the scale. I believe that through my Co-Op and other team activities, I have progressed from an acceptable team member to a desired team member. This semester I have progressed in my teamwork skills through my Co-Op, by balancing the needs of multiple companies simultaneously. I also had the opportunity to attend a teamwork conference in Seattle with the other three Co-Ops. This conference was immensely rewarding and I have already started applying what I learned there. Next semester I will be working on an IRE team for my final project.</td></tr>
<tr><td>Goals</td><td>Next semester I will be working on an IRE team after spending a year as a Co-Op. Although I did expand my teamwork skills while I was working for PolyMet, working on a team at IRE for my last semester will allow me to further develop my teaming skills. I would most like to work on:
1. Accepting and giving constructive criticism.
2. Learning when to assert myself as a leader, and when to take a more passive role.
3. Share responsibility and praise for all the team members' mistakes and good work.</td></tr>
<tr><td>Action Plan</td><td>1. I have specific actions I will take next semester in order to fulfill my goal to work on accepting and giving constructive criticism.
• The first step I will take will be to use the peer review form from Traci and Christine every week, not just the two assigned times.
• I also will work toward having an open communication in design reviews where we can openly discuss the strengths and weaknesses of the team.
• I will seek mentorship from the faculty, especially from my project facilitator. I will tell them to share any constructive criticism they have for me throughout the semester.
2. At the beginning of the semester when we develop the Gantt chart, each team member takes responsibility for certain tasks.
• I will assert myself on the tasks for which I am responsible.
• I will not undermine the leadership of others on their tasks.
• I will not interrupt when my teammates are talking, and be open to their ideas.
3. It is important to present the team as a united front.
• When there are mistakes made on my team, I will not place blame. I will say that the team made a mistake, not a particular person.
• When we have successes, I will attribute it to the entire team, and not try to accept personal praise.</td></tr>
</table>

4.4.6. LEARNING THEORY AND RELEVANT COMPONENTS PROFESSIONAL LEARNING

If a person were to describe a concrete mix in terms of its ingredients, it could be considered as being made up of coarse aggregate (rocks) and fine aggregate (sand) with a chemical mixture of cement and water filling in all of the fine gaps between the rocks and the sand. For analogy, if we were to look at design learning and technical learning as the rocks and the sand, then professional learning could be seen as the cement-water mixture. Professional learning fits in between and around, providing essential support for design and technical. The essential professional competency aspects of communicating, leading, managing, and acting professionally and ethically all happen in and around the design and technical learning, giving them strength just like the cement gives strength to the concrete. Professionalism is integral to supporting the learning of design and technical competences. The learning of professionalism also has both dimensions of Illeris' learning model – internal interactions and external interactions. Communication is key to professional learning and is essentially the vertical leg of external interaction. Internal interaction moves along the continuum of content to incentive. The PDP epitomizes this continuum. In the PDP, students have to describe the content of their learning and thus discuss its importance in their careers, followed by making plans for how to improve the learning of content and the why, all the while communicating this to their external audience. Yet again, the professional learning at IRE moves toward the center of Illeris' triangle.

The learning of professional competencies is highly constructive. The students use their development action plan with injections from external sources, such as workshops, printed or digital media, feedback from peers, and feedback from supervisors to construct their new professional identity and set new goals and action plans. This cycle repeats itself over four semesters, as students continue to build their personal professional identity and self.

While the nature of professional learning is quite different from the nature of technical learning, the principles of how it is learned are quite similar. Using the APA principles it can be seen there are cognitive/metacognitive factors, motivational/affective factors, developmental/social factors, and individual factors all associated with the acquisition of professional competence. While the domain is different, the learning factors are the same.

An attribute of adaptive experts is a proficiency at reflecting on thinking during the thinking processes. Educational environments that lead toward the development of adaptive expertise have students perform substantial reflection and metacognition. The PDP process, which is an essential component of the professional learning environment at IRE, is, by its nature, a reflective and metacognitive learning activity. Feedback from graduates and employers of graduates is that they are further along the developmental spectrum from novice to expert than are their peers from other learning models.

Scaffolding is key to all three domains of IRE learning. In the professional domain, new students are provided with much structure; whereas, graduating seniors are free from nearly all guidance. For those new students, faculty and more senior students act as role models, give guidance, and give feedback on expectations and levels of performance.

IRE students tend to be highly motivated by being recognized as professional practitioners of engineering work. There is a symbiotic relationship between identity and motivation, in regards to professional development. Motivation builds identity, which in turn tends towards more motivation.

The situativity of learning professionalism in situ with learning technical and design competencies, in contrast to learning the same skills separated from practice, provides for a deeper, longer lasting competence. As an example, most new engineers took a class in technical writing sometime during their education. However, that class was disconnected from the technical and design learning in their other courses. The skills from that course tend to be less accessible and less transferable than when the learning and feedback on technical writing takes place on the communication of the actual design, and technical learning happening in other courses. This is how technical-writing learning happens at IRE.

4.4.7. IRE SOCIAL CULTURE EXPECTATIONS

The IRE social culture is designed to be inclusive, collegial, and professional. One of the mottos at Iron Range Engineering is "we learn engineering by practicing engineering the way we will when we become engineering practitioners." As such, there is an expectation that all daily interactions between all members of the community will be at a professional level. The level of dress for all members of the community is business casual for most days, business formal when we have external guests, and college casual on Thursdays.

There is an expectation of shared ownership of the facility. Project rooms are expected to be clean and organized at the end of each day. Any person who uses the laboratory or common spaces is expected to leave the space neat and organized after its use.

Titles are not used in daily verbal communication. All members (students, faculty, and staff) of the community are on a first name basis. When discussing the importance of succeeding in a diverse environment, students are asked to define in what daily work environment they desire to work after graduation. The attributes tend towards welcoming, happy, positive, and encouraging. The social culture at

IRE is expected to have the same attributes. When visitors come to IRE, titles are used as a means of introduction.

Formal and informal student life events are an important aspect of the IRE social culture. There are formal student chapters of professional societies that meet frequently, giving students leadership opportunities, outreach opportunities, and deep career exposure. The staff member who coordinates student life organizes many trips, per semester, for the purposes of entertainment, exercise, or further industry exposure. Informal student life examples include student-led gatherings to work out, watch movies, or volunteer in the community.

Connecting to learning theory and learning environments, the social culture is composed of a collection of multiple learning communities that empower social constructivist learning. The interpersonal relations, communication, and social interactions influence the learning in all domains.

As Section 4.4 concludes, it is important to recognize the significant process that students go through from being the type of student they are when they enter the program compared to the type of self-directed learner they become. They will demonstrate deep areas of expertise within the design, technical, and professional domains. This process is the result of an intentional, purposeful, and guided set of experiences to authentically bring students to this point. Just as this process is different from the learning experiences from which the students come, so also it is different from the process by which most of the faculty and staff have experienced in their education and professional lives. Therefore, it is critical to be just as intentional and purposeful in guiding them through a set of experiences, which will allow them to be successful in this environment. Section 4.5 will focus on this aspect of the IRE model.

4.5. ACADEMIC STAFF AND FACILITATION ELEMENT

Given that most faculty will work more in silos with little “across course or discipline” interaction in most *discipline and teacher centered* approaches, there is limited need for preparation of the academic staff and need for collective facilitation of curricular elements within traditional education programs. In a more *innovative and learner-centered* curriculum, faculty will require a greater degree of academic staff coordination. Innovation means ongoing change in the organization and the culture and, as identified in Section 2.1, this always require equipping people to be successful in this new culture. A specific prevalent need for them to develop in a PBL curriculum is the role of being a project supervisor or facilitator (Kolmos, Du, Dahms, et al., 2008; Kolmos, Du, Holgaard, et al., 2008). Likely this is something they have never encountered before. Given the innovative nature of the IRE program, within the U.S. engineering context, and the program starting from a clean slate, this element is a critical part of the IRE model success.

Placement on Spectrum

A previously existing model, or program for facilitating faculty (academic staff) development, was not identified at the beginning of the IRE program development to provide them with the training they needed in their new roles. Instead, a choice was made to develop a continuous improvement model that would periodically identify and address areas for improving education approaches and practices. To facilitate this, the faculty were officed in a common faculty office space or office suite. The use of this innovative development process for the academic staff and facilitation, places the IRE model fully towards the *innovative and learner-centered* end of the spectrum, as shown in Figure 4.11.

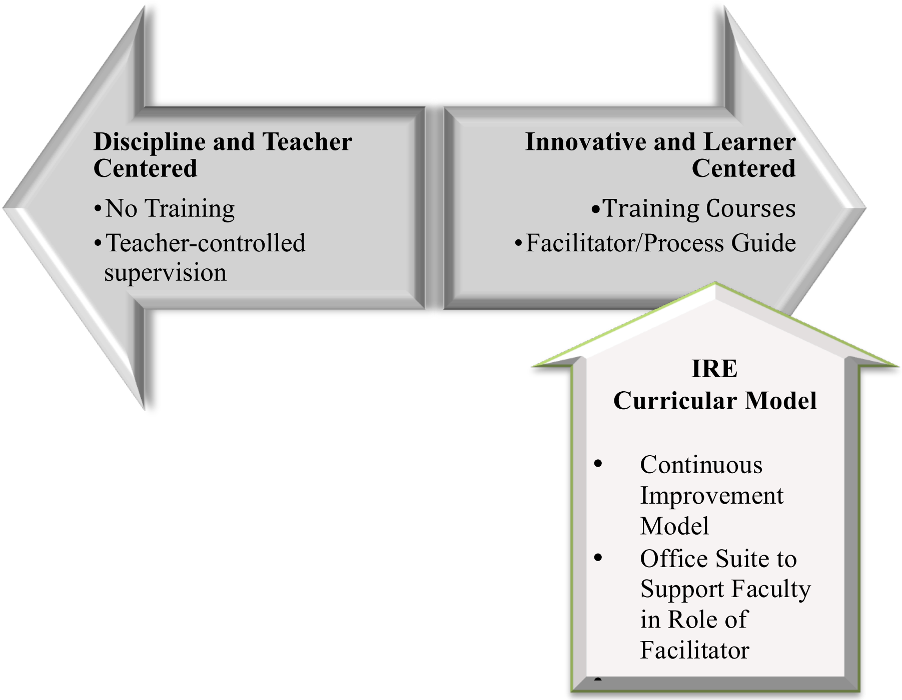


Figure 4.11. Academic staff and facilitation spectrum

In engineering practice, continuous improvement of products and designs is essential to remaining competitive. In a manner consistent with this professional practice expectation for students, the IRE PBL program has adopted that philosophy for academic staff to work together in a collaborative manner, as professionals, would in industry. This approach has resulted in a collaborative *continuous improvement approach* for IRE.

Characteristics of IRE Model

Since the first semester of operation in 2010, the program has continuously evolved, using a model that takes inputs from all constituencies. The program started by using ideas based on theories of how learning should work and by observing successful models that others have employed. Referring back to Schön's high ground vs. swampland, the program started on the high ground. Within days, the initial faculty found themselves in the swamp, having to deal with the realism of complexity that came with doing something the faculty didn't know how to do, and the students weren't accustomed to doing. The trajectory started with much openness and little structure.

The key to success, at the beginning, was openness by the program and the academic staff to listen to students, themselves, and the expert advisory boards. It was essential to analyze what was working, what wasn't, seek advice for change, and create new strategies. The technical, design, and professional learning described previously is the current evolution. It is slightly different than a semester ago and slightly different than a semester into the future, much different than two years ago and much different than it will be two years into the future.

The continuous improvement approach starts by inviting external guests to campus to observe learning activities and interact with students and faculty every semester. Regular visitors include highly recognizable experts such as Dr. Jeffrey Froyd, Dr. Denny Davis, Dr. Edwin Jones, Dr. Sheri Sheppard, Dr. Tamara Moore, the late Dr. David Jonassen, Dr. Rose Marra, and Dr. Carolyn Plumb. The total number of visitors each semester is usually above 5. Over 30 different external guests have been to visit. Each of these experts makes a report of their observations and suggestions for future improvement. Another set of external suggestions comes from an industry advisory board, comprised of engineers and managers from client partners. In the last week of each semester, a 90-minute open discussion is held with the student body. In small groups, they identify trouble spots and then develop suggested action plans for improvement. All ideas are collected. Individually, each staff and faculty member keeps a running list of her/his own ideas for improvement. Additionally, graduating seniors submit a "best works" portfolio including works that meet all of the performance criteria for each of the 14 student outcomes. These portfolios are scored internally and externally against appropriate rubrics. The results of this portfolio analysis, showing which outcomes are being met and which need to be addressed, are also an input to the continuous improvement process.

The day after the semester grades are submitted, the faculty and staff hold "Faculty Summit 1." At this summit, all inputs are categorized, discussed, and labeled as must do now, might do now, should consider in future semesters, or not possible/applicable. Faculty and staff divide the potential improvements and take responsibility to draft action plans.

In the week preceding the new semester, "Faculty Summit 2" is held. All of the action plans are presented and discussed. When consensus is reached on new improvements, they are put into the syllabi, student handbook, or faculty handbook, as appropriate. The improvements are presented to students at the opening session on day one of the semester and put into operation for the semester.

The cycle then begins again. Examples of processes that have undergone substantial change as a result of this process are the model used for design learning, physical spaces, presentation formats, the student metacognitive processes, student life opportunities, final exam formats, and many smaller changes. All suggested improvements are tracked, over time, in an observation-action-result table. See Tables 4.8 for an excerpt from an OAR table.

Table 4.8. Sample observation-action-result tracking table for continuous improvement

Observation	Action	Result
Have mentors review PIP of students from the previous semester to guide and monitor improvement	Faculty handbook	Pending
Continued support for dealing with teammembers who don't meet expectations. Goal is to not have people that no one wants to work with.	Not yet implemented	Pending
Attendance - keep attendance for all Professional and Seminar Activities that require Participation and Reflection grading.	Create Sheet For Attendence	Pending
A comprehensive way to integrate professional writing expectations into all graded documents. IEEE style required?	Not yet implemented	
Academic Integrity Policy - needs to be written, communicated to students, and applied	Needs to be written and added to the wiki	Pending
Faculty/mentors should provide written feedback on individual documents timely so there is plenty of time to integrate this feedback into Final Tech Document.	Encourage timely feedback from mentors	Not much change
Instruct on Linked In and other social media as job search tools.	Not yet implemented	
"Yellow sheet" - add a section for "Receives feedback and constructive criticism well" or not!	Added to the document	Pending
Instruct students on evaluating credibility of internet resources. Workshop on research methods using university databases and industry technical journals. Encourage students to verbalize original source rather than "I found this online"	Not yet implemented	
Emphasize talking like an engineer. Columns for each: 1) Normal Speak; 2) College Speak; 3) Engineer Speak; 4) Geek Speak. Worst offenders could be starred!	Done	Commendations from external visitors
Final Oral Exams: change topic each semester	The format has changed	No longer an issue
Create common technical document template similar to PDP template	Common syllabi were created	Helped with familiarity
Better define expectations for professional journal entries	Create the "four questions" to be answer in the journal	Students still need to be reminded to use them
Start doing sections of PDP and Outcome portfolio earlier in the semester	Create document day	Helped students stay on top of deliverables
Have a larger emphasis on team building before actual work on the project starts and throughout	Addressed in student life	Pending
Consistently enforce professional expectations	Addressed in faculty meeting	Still needs to improve
No "surprise" learning seminars (classes).	Encourage faculty to create a learning schedule	Added to syllabi

An essential element of the continuous improvement approach is the collaboration amongst the faculty and the consistency of messaging to the entire IRE community. The collaboration among faculty is facilitated by the summits mentioned above, but on a daily basis the common faculty office suite, Figure 4.12, creates a natural environment for faculty to collaborate informally on a daily basis. It provides support for faculty as they learn how to guide the complexities of student learning in the PBL curriculum.

The academic staff attends the weekly seminars, shown in Figure 4.13; providing an opportunity for all members of the IRE community, students and academic staff, to hear the same message regarding ideas such as professional development topics. This allows all academic staff to be able to reinforce those concepts, through learning conversations and informal dialogue, with students throughout the week.

Figure 4.12. Faculty office suite

Figure 4.13. Seminar room

Critical, to the development of the academic staff and their abilities to facilitate the teams and the student learning, is the continuous improvement approach and the physical space of the office suite. The physical space is just as critical to the student learning experience. Section 4.6 will look at the overall physical space and organizational structure of the IRE model.

4.6. SPACE AND ORGANIZATION

The physical space and institutional organization have to support the PBL curriculum. What is sufficient in the *discipline and teacher-controlled* curriculum will not be conducive to supporting a PBL curricular approach. Having administrative, organizational, and physical space fully supporting the PBL curricular model is essential to the *innovative and learner-centered* approach.

<u>Placement on Spectrum</u>

The Iron Range Engineering program is unique in that it started from the beginning, with administrative support, to build a new and innovative PBL model of engineering education. Shortly after starting, new physical space was constructed, and former space was remodeled to fit the new program. This allowed choices to be made, within budgetary limits, to develop a physical space that directly supports the curricular approach of PBL. The unique full-on administrative support and physical space construction (to support PBL) uniquely places the IRE model on the *innovative and learner-centered* end of the spectrum, Figure 4.14.

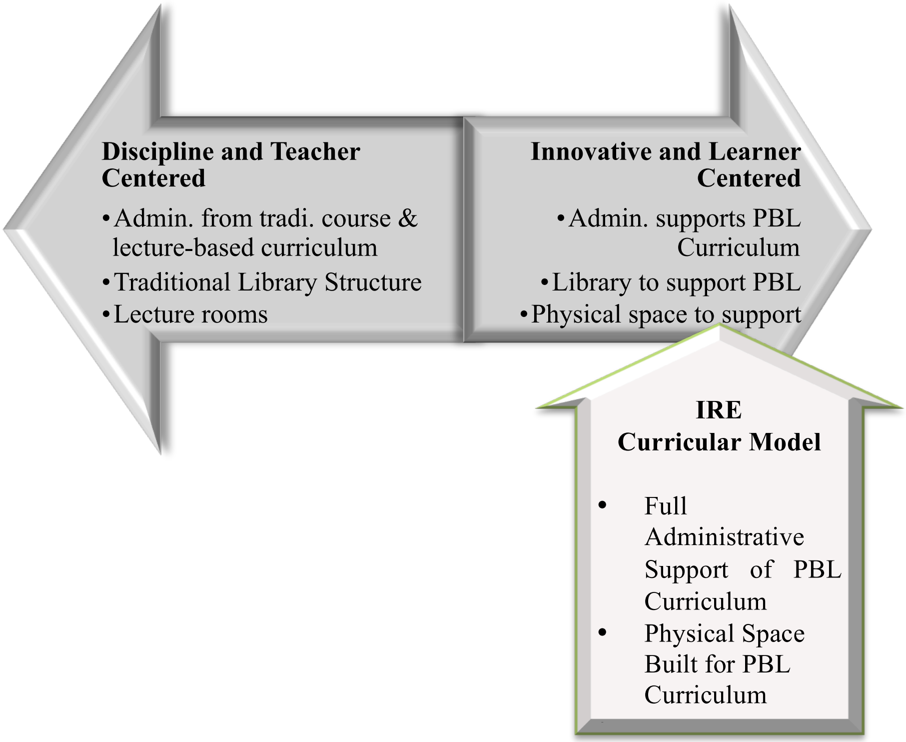


Figure 4.14. Space and organization spectrum

<u>Characteristics of IRE Model</u>

The IRE program has five different kinds of physical space: project team rooms, laboratories, community spaces, office suite, and the seminar room. See Figure 4.15 for layout of IRE physical space. Project rooms are modeled after the team rooms at Aalborg University. The purpose is to have a physical space in which students have their own offices, a place where the team has access 24 hours per day, 7 days per week to work on their design project or their individual learning.

> *"The group room (is) the physical field for accumulation of social and cultural capital. This process is individual as well as common and involves sharing of capital. Participating in the common accumulations process creates a feeling of belonging besides the 'competition' between group members for own values and ideas. In most groups this feeling grows stronger and stronger during the lifetime of the group and creates a positive attitude towards the learning environment. The learning environment is synonym with the project group environment." (Spliid and Qvist, 2007)*

Figure 4.16 is a photo of an IRE project room. Weekly design reviews take place in the room. The walls are filled with whiteboards and project oriented posters. Each student has his or her own desk and bookshelf. This proximity provides for substantial team interaction, which empowers team development and project advancement.

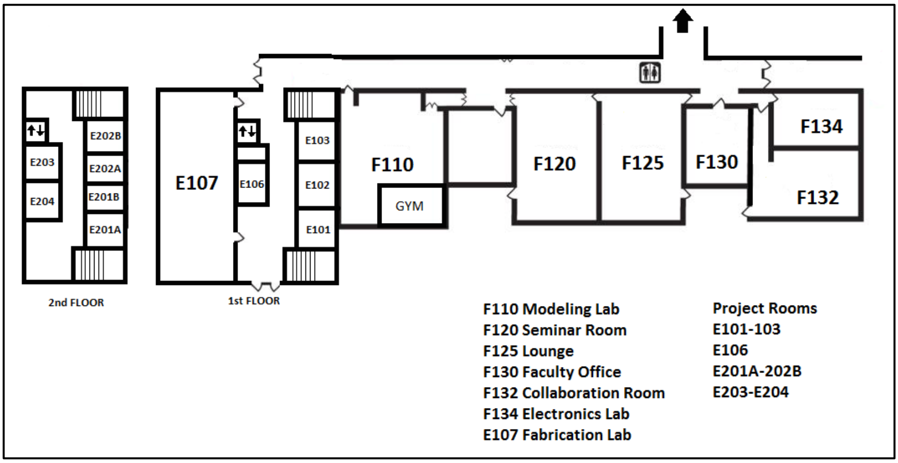


Figure 4.15. Layout of IRE physical space

IRE has three laboratory spaces: an electronics lab, a modeling lab, and a fabrication lab. The electronics lab (see Figure 4.17) is a traditional laboratory space in which students can learn and experiment with electrical, controls, instrumentation, PLC, and electronics concepts. The modeling lab (see Figure 4.18) is a modern conceptualization space for creating physical, non-working models, using devices such as a laser cutter or rapid prototyping machine. The fabrication lab (see Figure 4.19) is a large space for building working prototypes, using advanced fabrication tools such as CNC lathe, CNC mill, water-jet, manual mill, various types of welding, and a wide assortment of hand and bench tools.

IRE has several community spaces where students and staff integrate on a frequent basis to socialize, gather for learning conversations, or take part in student life activities. The spaces are a student lounge (see Figure 4.20), a small exercise room, and lobby spaces (see Figures 4.21 and 4.22).

The academic staff share one office suite (see Figure 4.12). Similar to a team project room, the office suite allows the faculty to regularly interact with each other in a synergistic way. Students are welcome in the office suite at all times, with the intent of having an inclusive student-faculty community.

The seminar room (see Figure 4.13) is the one place where the entire community gathers at one time. This usually happens three times per week. Monday mornings, from 08:00 to 10:00, students and academic staff gather for “seminar”, a class for professionalism workshops or student presentations. Wednesday mornings, students gather for practicing closed ended problem sets in preparation for their engineering licensing exam, which they will take near graduation. On some Friday afternoons, industry speakers join the program for a lunch prepared by the students, and then they give a 30-minute speech about their industry and their personal career.

The physical space supports learning through influencing the social factors, context of learning, instructional practices, identity, and community building.

Figure 4.16. Sample IRE project team room

Figure 4.17. Electronics laboratory

Figure 4.18. Modeling laboratory

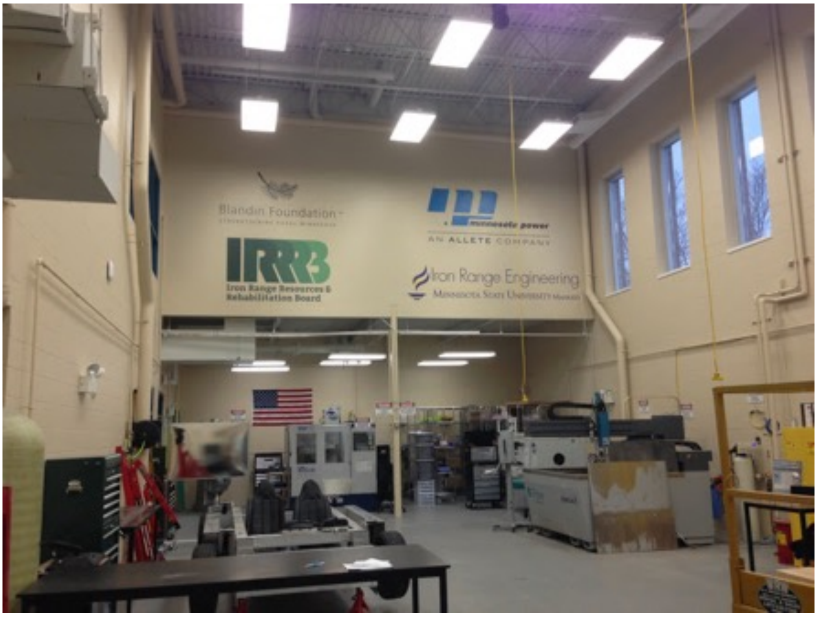


Figure 4.19. Fabrication laboratory

Figure 4.20. Lounge

Figure 4.21. Downstairs lobby gathering space

Figure 4.22. Upstairs lobby gathering space

4.7. ASSESSMENT AND EVALUATION

Assessment is a core driver in the student learning process. This final curricular element is important in understanding the placement of the IRE model with the PBL curricular model. As compared to the *discipline and teacher-controlled approach*, in which the assessment is focused primarily on the individual and the summative knowledge gained in a course, the *innovative and learner-centered approach* focuses on assessment that supports the collaborative learning of the project team. Thus, the assessment focuses on the team being assessed while still maintaining the grading of individual performance. Formative assessment methods are a critical part of this assessment process and keep a focus on the student awareness of the learning process.

Placement on Spectrum

A choice was made in the development of the IRE model to develop an assessment and evaluation practice that supported the ideals of the *innovative and learner-centered approach.* It focuses specifically on oral exams, group assessment, and formative assessment tools and methods. This places the IRE model on the *innovative and learner-centered* end of the spectrum, as shown in Figure 4.23. The assessment of the design, technical and professional competencies will be discussed in this section.

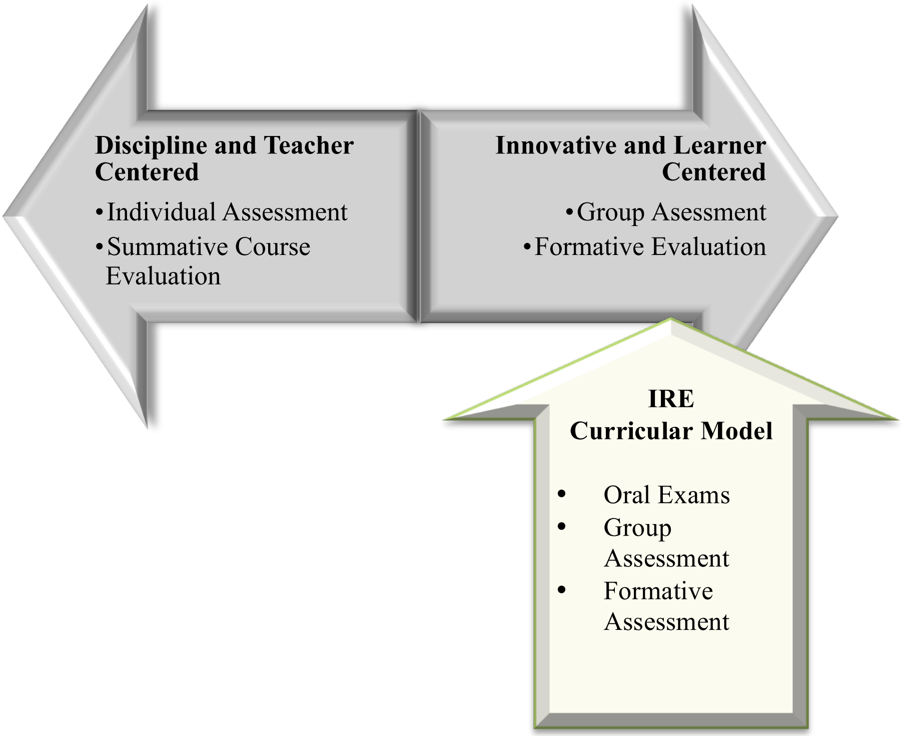


Figure 4.23. Assessment and evaluation spectrum

<u>Characteristics of IRE Model</u>

This section will specifically look at the IRE model approach to assessment of the design, technical, and professional competencies. The learning activities that empower students to achieve growth in these competencies will be identified.

4.7.1. DESIGN ASSESSMENT

Formative assessment happens in the weekly informal design reviews. The facilitator provides developmental feedback on all aspects of the project execution and documentation. Project teams are evaluated based on the quality of the written design documents, the quality of their formal presentations, and the quality of the client deliverable(s). Panels of academic staff grade the documents and presentations to allow for consistent grading from team to team. In addition to the team grade, the project facilitator assigns an individual grade to each team member that reflects the level of contribution and professionalism he/she brought to the team. This aspect prevents “passengers” from achieving the same grade as their team when they may have contributed much less to the team deliverables.

4.7.2. TECHNICAL ASSESSMENT

Throughout a course, the faculty member provides low-stakes, formative feedback on the students’ performance on daily assignments and conceptual understanding. The required components in a technical competency from a grading standpoint are these: DLA, technical evidence (notes, problem sets, concept maps, etc.), reflection journal, metacognitive memo, and an oral examination. The weighting of how much each of these components contributes toward the grade is a collaborative decision between the student and the instructor, made during the syllabus creation at the beginning of the block. Student input is given in an effort to provide them with ownership and control over their own learning. Grading is again of the five-point scale, from 1 (weak) to 5 (exemplary). The scale is applied to each deliverable. Table 4.9 shows an example of the rubric for the grading of a technical competency component.

The oral examination is a culminating one-on-one event at the end of the competency. Here the student defends their semester learning by answering questions regarding conceptual understanding, the integration of the new knowledge into the project or other DLA, and his metacognitive development. The oral exam process enables faculty members to pursue the boundaries of the students’ knowledge and provides students practice in the important skill of verbalizing their understanding of technical knowledge. It drives towards demonstrating understanding rather than presenting memorized sets of information. Students have the opportunity to go down a wrong path, be questioned about the path, then recover and find the right path. When the Iron Range Engineering program was evaluated by an external agency, one of the greatest strengths identified was the oral exam process.

Table 4.9. Sample grading rubric for component of technical learning

	1 = Deficient	**2 = Weak**	**3 = Acceptable**	**4 = Desired**	**5 = Exemplary**
Describe concepts in an oral exam Weight _______	Does not identify key concepts even with much prompting, or explanations reveal serious	Incompletely identifies key concepts with much prompting or explains them inadequately for proper	Correctly identifies key concepts with minor prompting and reasonably describes them both verbally	Correctly identifies key concepts without prompting and explains them well both verbally and	Promptly identifies key concepts and explains them contextually with skillful use of language and

	misconceptions	understanding	and symbolically	symbolically	symbols

4.7.3. PROFESSIONAL ASSESSMENT

In each semester, the students evaluate their current level of professional performance, providing evidence of their judgment, set goals for improvement for the next semester, and write an action plan for achieving the goals. Table 4.10 shows the scale students use for these self-analyzes.

Table 4.10. Professional development plan self-assessment scale

1 = Deficient	2 = Weak	3 = Acceptable	4 = Desired	5 = Exemplary
Shows little evidence of desired performance, clearly not acceptable for IRE graduates	Shows some but inadequate evidence of desired performance needed in IRE graduates	Shows moderate evidence of desired performance, minimally acceptable for IRE graduates	Shows strong evidence of desired performance, clearly meeting high expectations of IRE graduates	Shows unusually strong evidence of performance as a skilled professional, exceeding expectations of IRE graduates

Every semester there are several learning activities that empower students to achieve growth in each of these areas. These learning activities include the following: workshops by external experts, workshops by IRE academic staff, peer discussions, assigned readings, student presentations, videos, and personal reflection. In addition to learning opportunities, there are multiple methods for feedback on development. Examples include daily informal feedback from faculty to students, formal peer reviews, formal personnel evaluations from project facilitator to each team member at the end of the semester, and grading of various professional documentation submittals. The PDP is a comprehensive document; wherein, each semester the student adds her or his new assessments, goals, and action plans allowing for visible changes in development throughout the education.

4.8. CURRICULAR CLASSIFICATION OF THE IRE PBL MODEL

Beyond the classification of the curricular elements of the IRE PBL model with curricular elements of a PBL curriculum done in Sections 4.1 through 4.7 above, the analysis continues with a curricular classification through a synthesis of the curricular components of Section 2.2 from Biggs & Tang (2011), Jamison et al. (2014), Sheppard et al. (2009), Cowan (2006), Rompelman & de Graaff (2006), Kolmos and de Graaff (2014), and Beanland & Hadgraft (2013). From these works, a framework for classifying engineering curricula was developed. It consists of more than 25 questions, the answers to which create the picture of any engineering curriculum. Presented in this section will be the answers to these questions in regards analyzing to the Iron Range Engineering PBL curriculum. These questions provide another perspective to view the program.

Is there a higher emphasis on knowing, acting, or being? Or are they valued equally?

Iron Range Engineering students are encouraged to develop their own priority system with regard to knowing, acting, and being. The flexibility of project selection, team selection, and diverse choices in technical learning allow students choice. Those who may desire to go to graduate school have the opportunity to focus more deeply on KNOWING. Those whose passion is to use their engineering skills to impact the environment or societies can focus their choices towards BEING. However, the Iron Range Engineering program as a whole is focused on ACTING. The majority of students want to be practicing engineers in industry. The daily learning activities of students are focused on practicing engineering the way it will be done after graduation in industry.

Is the program scientific, entrepreneurial, or ecological? Or hybrid imagining?

As Jamison et al. (2014) describe these first three classifications, IRE would meet the classification of entrepreneurial. At IRE, a wider spectrum of skills and abilities are valued. In addition to technical acumen, abilities to design, communicate, lead, invent, and, overall, become a practicing professional are the attributes desired in the graduates. However, while the graduates tend toward careers in practice, the values of the program, as seen through the learning experiences of the students, lean towards the *hybrid imagining.* At IRE, we place equal emphases on "the scientific knowledge that is emphasized in the academic approach (in technical domain) and the practical skills that are emphasized in the market driven approach (in design and professional domains)", while emphasizing "social and cultural understanding" (in the professional domain). Examples of the emphases in the social and cultural domain can be seen in the development of several student projects focused on making lives better for people in need, in the substantial outreach volunteering that students do every semester, and in the learning activities focused around the student outcome of learning to succeed in a diverse environment.

What are the intended student learning outcomes?

There are 14 intended student outcomes described in Section 4.1.

To what level do they align with the Washington Accord? The IRE graduate outcomes meet all of the Washington Accord outcomes, with, perhaps, the exception that the WA places higher emphasis on sustainability than do the IRE outcomes.

To what level is instruction aligned with outcomes? The instruction, as detailed in all syllabi, aligns extremely well with the outcomes. The assessments at the end of the courses, when grades are determined, are strictly aligned with the outcomes. The rubrics for the outcomes are the rubrics for the course grading.

To what level is enactment aligned with outcomes? While not equaling the high level at which the instructional design is aligned with the outcomes, the instruction enactment approaches that level. Differences between design and actual enactment can be seen when some instructors and students fall back towards a more lecture-focused, deliverable-focused mode of operation, rather than a learning-focused mode. This is normal, considering it is the fallback position that all the students and instructors knew before they came to IRE. The IRE continuous improvement model, described in Section 4.5, provides a mode for continual reflection and realignment with intended graduate outcomes.

Is identity-building an intended learning outcome? While not stated as a graduate outcome, the entire model is focused on the students believing they are engineers-in-training. The activities that build identity include these: the professional expectations of an IRE student (see Section 4.3); the ownership in decision making about which projects to choose, which teammates to select, when to take core competencies, and designing their own set of advanced technical competencies; professional interactions with real engineering clients while performing real engineering design work; and the overall expectation that the entire learning experience is preparing them for engineering practice, all lead students to developing their personal identity as engineers.

Are intended learning outcomes realized as actual student outcomes?

Both the individual student and the program, as a whole, explicitly focus on the graduate student outcomes. The outcomes are stated in each syllabus. There are posters throughout the physical spaces detailing the outcomes and performance indicators. Instructors emphasize, and students buy-in to the belief, that the outcomes are the expectations at graduation. Students create portfolios and professional development plans that track their growth in each outcome, during each of their four semesters.

Is there a continuous feedback system to ensure alignment of intended outcomes, instructional design, program enactment, and course enactment with actual student outcomes? Yes. Described in Section 4.5 is the IRE continuous improvement program. A component of this continuous improvement program is the collection of outcome portfolios from each graduating senior. The submittals for each outcome are sent to the external national advisory board of Froyd, Davis, Litzinger, Sheppard, and Jones. In pairs, they grade the outcomes, using the rubrics to determine to what level the IRE graduates are meeting the intended outcomes.

To what levels is the alignment achieved? The gap between desired level and actual achievement level continues to shrink each year. Early gaps were accentuated due to the poor ability of students to select and describe how their works met the outcomes, leaving the reviewers with a lower view of alignment than actual. Those issues have been overcome and gaps now are more realistic. IRE graduates tend to exceed expected levels in design and professional outcomes while being at, or slightly below, expected levels in technical outcomes.

Are the needs of the student addressed in the curriculum design and enactment?

To what level is motivation for student learning considered in the design and enactment of the curriculum? The IRE curriculum uses professional identity building, real engineering context, and substantial opportunities for students to have choices in their education, all in an effort to build motivation for student learning.

To what levels are students included in the decision making of learning activities? They give input to what kinds of projects will be sought in an upcoming semester. They choose the project they on which they will work. They select their teammates for design projects. They determine when they take which core technical courses. They have input into the design of the syllabus in every one of the 32 technical courses. They create the set of 16 advanced technical electives they will take, often choosing a specialty course that has not been offered in the program before. They are an integral part of the twice-yearly continuous improvement process for the program.

To what levels do faculty involve students in analyzing their progress in achievement of their learning outcomes? Students track their progress of achievement in their professional outcomes through the continuous maintenance of the professional development plan. Each semester, students compile best practice submittals for the outcomes portfolio. The students analyze their own submittals against the rubrics to gauge their own achievement of the outcomes for all domains: technical, design, and professional.

Does the curriculum design/enactment align with exemplary practice?

To what level does the curriculum align with professional practice? All daily activities are designed to align with professional practice. This is exemplified by the students' professional development plans, requirements to live up to the professional expectations of an IRE student, periodic professional personnel evaluations, and interaction with real clients on real projects. All in an effort to develop their identity as a professional engineer.

Is PBL used? To what level? Yes. The entire curriculum is PBL.

To what level does the curriculum have and enact a professional spine? There are three credits of professionalism in each semester of the curriculum. Every week, students take part in professionalism workshops. They are made explicitly aware of the professional outcomes and track their own development in each outcome. The development of professional competencies is a weekly part of thee student conversation with their team facilitator.

Where does learning fall on the continuum of lecture/receiving to student-centered/active/constructive? All learning is designed to be student-centered/active/ constructive. In practice, about 90% of learning is executed in this manner with 10% falling back towards lecture/receiving.

How is physical space allotted for student-centered learning? The physical layout (see Section 4.6) is designed exclusively for student-centered learning, with space dedicated to student project teams, full access to labs, and interaction between small groups of students and instructors.

How is assessment conducted? Formative/Summative, Individual/Group There is substantial formative assessment provided by academic staff to students and to students from their peers. Summative assessment comes at the end of each term when grades are assigned. Though, there is a formative atmosphere in which students can continue to improve their grade in any technical competency until graduation. The PDPs and personnel evaluations are formative in nature. Design teams receive formative feedback at each weekly design review and summative assessment at the end of each semester. Technical and professional assessment is primarily individual; whereas, design assessment is primarily group.

To what level are students treated as student engineers? In every sense of the meaning, IRE students are treated as student engineers rather than engineering students. They are given responsibilities and ownership at a level approximating those of new practicing engineers.

To what level do teaching faculty share and explicate a common view of professional practice? All faculty are involved in developing and executing the professionalism syllabus and expectations, as well as in performing formative and summative professionalism assessment. However, issues frequently arise wherein a small number of staff members exhibit behaviors that are counter to the expectations of students. In these instances, faculty credibility is damaged, as well as is the overall belief by students that the expectations are achievable. This is a substantial hurdle that the program fights to minimize.

To what level are students exposed to practicing professionals? At any one time, at least two of the project facilitators are licensed professional engineers with substantial industry experience. The infusion of these professionals into the program, to interact with the students and academic staff, brings a higher level of understanding of professional practice. In addition, each team interacts frequently with their industry clients and several times per semester, practicing professionals are brought to campus to share their experiences.

Does academic staff receive training in facilitation? Yes. Aalborg University personnel have trained the IRE director in facilitation and, in turn, the director trains facilitators. In one instance, an Aalborg University member came to IRE to provide facilitation training to the facilitators. Each week, the facilitators meet for one hour to discuss topics and methods for facilitation that are appropriate to the week's activities.

To what level is reflection used in student learning? Are students given feedback on their reflective abilities? All students maintain a reflective learning journal in each of their technical competency learning experiences. These reflections are summarized in a metacognitive memo that students write at the mid-term and end of each semester. Technical instructors give feedback on reflection throughout the course of the competency. Reflection is central to the PDP process (see Section 4.4). At this point in time reflection is underutilized in the design learning.

Are academic staff trained in giving feedback on reflection? No. This is a missing component in the program, at this time, which should be addressed.

How are fundamental principles interconnected with each other and engineering practice? The central theme in each of the 32 technical competencies is the identification of the appropriate fundamental principles, understanding of the principles at a conceptual level, and connectivity of the principles to other principles, the semester design project, and the student's future engineering career. These connections take place during learning conversations, the creation of concept maps, the student's personnel journal reflections, and in oral exams.

Is a spiral model implemented for the learning of fundamental principles? The spiral model is central to all learning at Iron Range Engineering. Students are first exposed to the fundamental principles in their lower division courses before they get to IRE. Then, as they take core courses, these fundamental principles are revisited, interconnected, and connected to engineering practice. As the student's time at IRE continues, they spiral up as new projects or advanced technical competencies return to the use of the fundamental principles. For example, a typical student emphasizing in mechanical engineering will go through nearly 10 loops on the spiral for the fundamental principle of the conservation of energy. The students experience four loops of the professionalism and design spirals as they traverse their four semesters.

4.9. CONCLUSION

In Chapter 4, the Iron Range Engineering project-based learning model has been classified and analyzed with two different curricular models. The PBL curricular model, Figure 4.24, allows the IRE model to be compared to other models of PBL. The second curricular model, from Section 2.3, allows for a comparison of the IRE model to other models for engineering education.

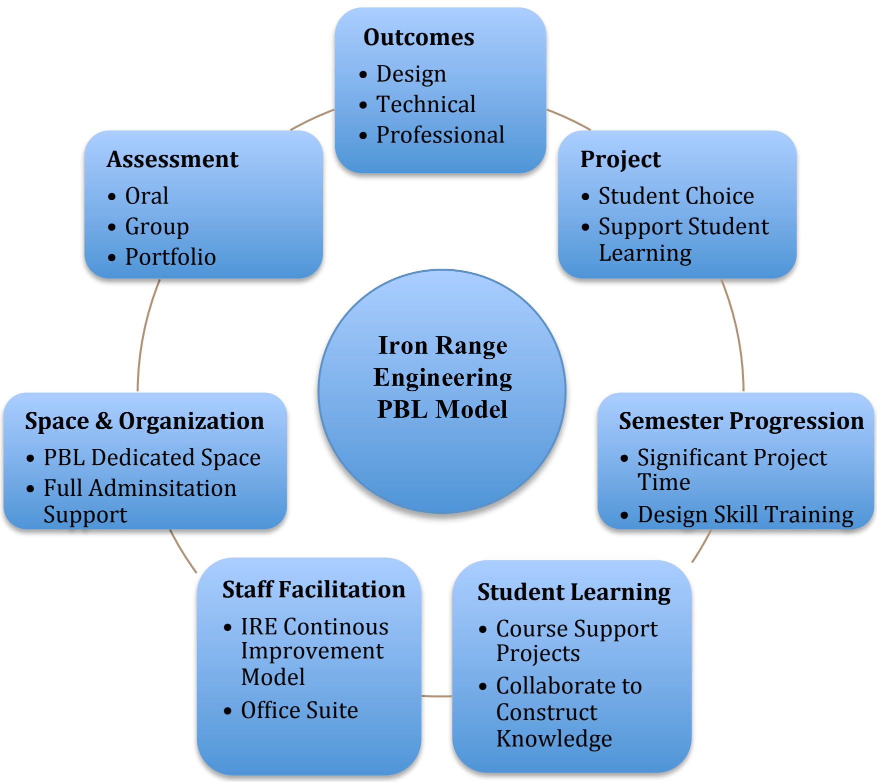


Figure 4.24. Iron Range Engineering PBL curricular model

Each spring, we spend six weeks of our time tapping maple trees, collecting sap, and boiling the sap down into syrup. During this process, it takes 40 liters of collected sap to harvest just one liter of syrup. As we look back over Chapter 4, we see a great deal of information (many liters of sap). All of this information is vital in describing and analyzing the IRE PBL curriculum. However, to get to a concise description of the curricular model, we use this analogy of seeking and yielding the 1-liter of syrup. It is in the distinguishing characteristics of the Iron Range Engineering PBL model.

The distinguishing characteristics can be described from the perspectives of the following: technical learning, design learning, professional learning, and the characteristics of the overall program.

Technical learning

Students learn the technical knowledge in "flipped-classroom" learning conversations rather than in lectures. In this way, the students watch a short video lecture (10-15 minutes) prior to class. Then in the class session, through questions and answers, conversation is held to assist the student develop her own conceptual model of the fundamental principles.

Each of the 32 1-credit technical competencies includes a process-learning DLA (deep learning activity). In these activities, students design experiments or some similar activity where they make a hypothesis, build experimental setups, collect data, analyze data, compare actual results to predicted results, and prepare a written report. Students complete 8 DLAs per semester for each of their four semesters.

Oral exams are a hallmark of the program. Each student takes an oral exam where he describes his conceptual and problem solving knowledge for each competency (8 per semester). Some oral exams are individual and some are in the form of small group exams.

Open-ended problem solving is practiced throughout each semester. In this activity, the students are given open engineering problems that require a broad set of inter-disciplinary knowledge to solve. They are given a final oral, one-hour exam at the end of each semester.

Design learning

Projects last one semester. Each project includes a team of 3-8 members, a team room, and a facilitator (either a practicing professional engineer or a staff member). Industry clients or student entrepreneurs propose the projects. The projects are authentic. In other words, staff members do not reformat the projects. Students interact directly with their client. The facilitator stands to the side and facilitates student learning rather than standing between the client and the group as a liaison. The teams create extensive written documentation and give 6 technical presentations. Three times per semester the team goes before a review panel to defend their work and work processes.

Professional Learning

Each semester the students undergo a wide variety of professional learning workshops on topics such as presenting, contemporary issues, technical writing, ethics, leadership, team conflict, inclusivity, learning about learning, and professional responsibility. They then put these professional skills to work in their learning environment, which is designed to model the environments from professional practice. In this environment they face high levels of expectation of professional responsibility.

Each student writes a professional development plan (PDP) wherein they write goals for development of their professional competence. They also write action plans as roadmaps for accomplishing the goals. Throughout the semester they receive formative feedback from each other and academic staff on their performance in their goal areas. They reflect on their performance and developmental progress as the semester progresses and again at the end of the semester. The final reflection results in a set of new goals for the upcoming term.

The key to professional learning is a personal motivation whereby personal autonomy is valued and practiced as students achieve competence in a connected environment. A common statement at IRE is that "students create a trajectory of development to the engineer they want to become." The resulting motivational levels are high and professional development is highly valued by the students and their community of learners.

Overall program distinguishing characteristics

Adapted from the Aalborg model is the concept of "team rooms" or "project rooms." In this space, students have 24-hour access to an office they share with their project teammates. Through daily interactions, they organize their project, manage their interactions, and attempt to manage a collegial atmosphere. This space mimics engineering practice.

Reflection is embedded in the learning experience at a great depth. Students write three reflections per week on their daily experiences and development. Students write a technical competence related reflection each time they attend class. The PDP is a reflective document by nature. At the end of each half-semester, students write a reflective metacognitive memo wherein they analyze their learning processes and regulate their future learning. All members of the IRE community value reflection.

Continuous improvement is a way of life. The program embraces continuous improvement as a model for making substantial changes to the learning model each semester. The faculty members apply continuous improvement to their teaching. Students apply continuous improvement to themselves as emerging professionals and self-directed learners. The community values the power of continuous improvement in engineering design and applies it every juncture within the learning model.

Finally, a last distinguishing characteristic is the act of being explicit. Much learning in their lives prior to entering the program was implicit. It was implicitly expected that if they passed a calculus class with an A grade, that the student would bring forward the relevant calculus knowledge to her future learning and engineering practice. The result of the implicit expectation is that the requisite knowledge was often not brought forward. At IRE, all expectations are explicit and reinforced through continuous expectation as well as continual feedback on development progress.

<u>Key Findings:</u> This set of distinguishing characteristics of the curriculum, developed from analyzing the IRE model, adds to the greater engineering education knowledge in how a curriculum can be developed to meet the calls for change. It also develops a greater understanding of student learning within this model of project-based learning. The results can be considered by engineering education and those individuals involved with curricular change decisions to better understand project-based learning, especially within the U.S. engineering educational context.

The distinguishing characteristic of being explicit is in itself a key finding. The development of the curriculum identified the potential power that making learning outcomes explicit has for empowering students in attaining learning and program outcomes. This commonly underutilized aspect has potential to be used in any curricular models within engineering education, not just PBL.

VOLUME 1 CONCLUSIONS

Volume 1 is a description and analysis of the Iron Range Engineering PBL program from four distinct perspectives: calls for change, theoretical, historical, and descriptive analysis of curriculum. First, the new model of PBL education was framed in terms of the calls for change in engineering education (Chapter 1) and then change theory, curricular theory, learning theory, and PBL theory (Chapter 2). Upon completion of the theoretical underpinning, the models of change theory were to be used to describe and analyze the historical development of the Iron Range Engineering program (Chapter 3). Finally, the PBL program was fully described and analyzed in terms of the curricular, learning, and PBL theories (Chapter 4).

The ultimate purpose of volume 1 was to identify aspects of the change process and the developed curriculum that are of interest to the greater engineering community for meeting the calls for change and for developing a greater understanding of student learning within this model of project-based learning. It is intended to enable curriculum developers and decision makers in contemplating and implementing a curricular change process. In addition, volume 1 provides an extensive background and develops the focus for our individual volume 2 editions where we design and conduct research studies on the self-directed learning (Ulseth) and professional competency development (Johnson) of the students in the IRE program.

Summary of work completed

First, we highlighted the calls for change in engineering education (Chapter 1). These calls aim for a better alignment between the knowledge and skills desired in engineering graduates and the learning activities and processes in the engineering curricula. Many of these calls served as an impetus for the start of the IRE program. In particular, Sheppard et al., (2009) served as both impetus and guide when the program began in early 2010.

Next, was the process of creating theoretical frameworks. In regards to change, we developed a case to use Froyd's organizational change model and the dual-layer curricular change model from Kolmos and de Graaff (Chapter 2.1). These two models served as the structure in providing the historical context of the Iron Range program.

An analysis of curricular theory (Chapter 2.2) resulted in the development of a framework consisting of more than 30 questions that, when answered, characterize a curriculum in multiple dimensions. The many sub-questions fall under the following main questions:

- Is there a higher emphasis on knowing, acting, or being? Or are they valued equally?
- Is the program scientific, entrepreneurial, or ecological? Or hybrid imagining?
- What are the intended student learning outcomes?
- Are intended learning outcomes realized as actual student outcomes?
- Are the needs of the student addressed in the curriculum design and enactment?
- Does the curriculum design/enactment align with exemplary practice?

The answers to all of these questions give a program a unique "finger print." The ability to describe a curriculum to this level of detail enables curriculum developers the ability to understand the attributes of the curricula in ways that would allow them to contemplate its potential values for adaptation. The ultimate goal of the section was to use this framework to analyze the Iron Range Engineering program in these dimensions.

In learning theory (Chapter 2.3), we started by describing Illeris' model (2007) and then used Bransford (2006; 2000) and Sawyer to give validation to Illeris' model. We then, presented a discussion on constructivism as the primary theory of learning on which modern views of best practice are built, and included the constructivist-based American Psychological Association's learner-centered psychological principles. We followed up with descriptions of the following relevant components of learning and learning environments: development of expertise, reflection, metacognition, scaffolding, motivation, situativity, learning community, and identity. Ultimately, we presented a synthesis of the work in order to build a framework to analyze the Iron Range Engineering model in Chapter 4.

The final theoretical discussion and framing took place on PBL (Chapter 2.4). We embraced the curriculum model that is based on the PBL learning principles and on the curriculum theories of alignment and social construction. The PBL curriculum model is linked to the PBL principles. The seven elements are as follows:

- objectives and outcomes,
- types of problems, projects, and lectures
- progression, size and duration,
- students' learning,
- academic staff and facilitation
- space and organization, and,
- assessment and evaluation" (Kolmos & Graaff, 2014)

We identified that each of the elements of this PBL curricular model has a broad spectrum from a teacher-controlled on the one side to an innovation and learner-centered approach on the other side. Between each of the ends of this spectrum are several degrees of varying, mixed approaches that can be applied in the development of a PBL curriculum. We then created a visual model for placing the IRE PBL curriculum on the continuums for each of the elements with the intent of applying the model in future chapters.

The history of the development and implementation of the Iron Range Engineering program was told in-depth (Chapter 3). The framework for the history came from applying both of the change models identified in Section 2.1. The data for the story came from a wide variety of conference papers, magazine articles, and newspaper articles published on the IRE program over the many years that development and implementation took place. Early beginnings of the program came out of the successes at Itasca Community College engineering program in Grand Rapids, Minnesota. The history starts with a detailed description of that program showing how its elements would serve as the seeds that would grow into many of the elements of IRE. The history further details how the needs of the region resulted in the program's funding. The influences of a national advisory board and the Aalborg University model were included. Finally, the history is told through the program's ABET accreditation and up to the present day.

The build up in volume 1 was towards a full description of the IRE model of project-based learning (Chapter 4). In great detail, the program was described and analyzed from many perspectives. Using the elements of PBL curriculum identified in Section 2.4, the information was organized into sections for: objectives/outcomes, problems/projects, progression/size/duration, student learning, academic staff/facilitation, space/organization, and assessment/evaluation. The curriculum focuses of professionalism, design, and technical learning were described. Finally, the frameworks for classifying developed in Chapter 2 were applied to the program to show its attributes at levels of fine detail.

Findings

The analysis of the IRE PBL model identified key findings from the change process and the developed curriculum that are of interest to the greater engineering education community:

- the successful curricular change process,
- the distinguishing curricular aspects of the new PBL curriculum,
- the explicit focus on student attainment of design, technical, and professional competencies, and
- the two taxonomies for analyzing a PBL curriculum; the arrow spectrums from the PBL elements and the 30 curricular questions from the learning theory.

In this section, the findings will be analyzed in terms of the potential for further study.

Successful Curricular Change Process

The history of Iron Range Engineering is a story of a successful curricular change process as viewed through the perspectives of organizational change and management of educational change. It is bottom-up in its creation as a new entity; its ideation, development, and continuous improvement being driven by faculty. It is top-down in its creation as a department in the College of Science Engineering and Technology at Minnesota State University, Mankato and support by top-level leadership at the institutions involved. Success of the start-up is evidenced by the continued existence and current vibrancy of the program. Section 2.2 of this thesis identifies and describes essential attributes for change to succeed:

- Need for both external and internal drivers
- Leadership team
- Vision casting
- Empowering people to act
- Formative evaluation

These attributes are critical elements in the change that was accomplished and can be used in consideration of change within other engineering programs in the U.S and add to the knowledge of change in engineering education.

In regards to further study, this topic has been analyzed extensively in Volume 1 and through external research by a team who has studied the impediments to change. This work identified the additional opportunities for study of each of these elements in finer detail. By characterizing the nature of each element in studying the implementation at a deeper level, more knowledge of the process could be gained and shared.

Distinguishing curricular aspects of the new PBL curriculum

A description of the new PBL curriculum is contained in its positioning within the curricular elements of PBL and through the set of distinguishing curricular elements developed from analyzing the way in which the IRE model meets the calls for change. The distinguishing curricular elements are grouped within the design, technical, and professional competencies:

- Technical Learning
    - Flipped classroom – Learning Conversations
    - Deep learning activities in each course
    - Oral exams
    - Open-ended problem solving
    - Self-directed learning skill development

- Design Learning
    - Authentic industry problems
    - One-semester projects
    - Extensive verbal communication of design progress
    - 3-8 person teams
    - Facilitation
    - 3 design panel reviews per semester
- Professional Learning
    - Professional Development Plan
    - Personal trajectory in professional development
    - Engineering practice environment
    - Professional expectations
- Overall Program
    - Team rooms
    - Reflection throughout
    - Continuous improvement
    - Explicitness
    - Continual feedback to students

In regards to further study, the distinguishing curricular elements within the design, technical, and professional competencies have been described in terms of approach, how they are underpinned by theory, and the potential for success. The student development for and attainment of the competencies within these categories for this PBL program needs further study. They could be studied as a whole or for each individual category.

<u>Explicit focus on student attainment of design, technical, and professional competencies</u>

One additional distinguishing characteristic is the act of being explicit. Much learning in the student lives, prior to entering the program, was implicit. The result of the implicit expectation is that the requisite knowledge was often not brought forward. At IRE, all expectations are explicit and reinforced through continuous expectation as well as continual feedback on development progress.

In regards to further study, the act of making student attainment of competencies explicit is of value for further study. This aspect of the curriculum has potential for implementation in a wide variety of engineering education learning models to improve student learning.

<u>Two taxonomies for analyzing a PBL curriculum</u>

The study of the IRE PBL program led to the development and analysis of the program with two taxonomies for characterizing a PBL curriculum. The arrow spectrums from the PBL elements and the 30 curricular questions from the learning theory allow for various PBL curriculums to be analyzed and positioned compared to one another. The intent is to not rank models in comparison to one another, but to understand the different curriculums as PBL is applied in different social and education contexts. As PBL is implemented more widely, it provides "language" for comparative discussion as individuals involved with curricular change seek understanding.

In regards to further study, the use of these taxonomies on different models and the subsequent continuous improvement activities are needed. These taxonomies are at the initial version stage and further study and development are needed for them to fully benefit engineering education.

Closing comments

This completes volume 1 of these theses. It is a descriptive analysis of the Iron Range Engineering PBL program from four distinct perspectives. Key findings of interest to the greater engineering education community, from the change process and the development of the curriculum were identified along with potential topics for further study.

The shared work ends at this juncture. The act of completing this volume feels like an open circle has finally been closed. For over 10 years, we have been developing and implementing the IRE PBL model. For this entire time, the focus was on the next iteration of continuous improvement to implement. The need to apply theoretical constructs to our work was never important enough to do. We often chide our students for performing "garage engineering" where they complete their designs simply from intuition and innate ability, never taking the time to relate their work to the fundamental principles of engineering. We preach that the power of engineering emerges when their abilities are bolstered with the science. We designed and implemented the IRE model working as "practitioners" utilizing "best practices" and intuitively developing innovative approaches without fully understanding the theory behind them.

That is no longer. This volume has resulted in completing that work of developing the theoretical underpinnings of the IRE PBL curriculum. So many things that worked or didn't work now make sense. Our ability to understand and disseminate the work is now much improved. Each of us now moves forward with the contextual background from this extensive work, as researchers, into our individual studies in volume 2.

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VOLUME 2 INTRODUCTION

In the previous volume, the Iron Range Engineering PBL program was analyzed. The purpose of providing the background was to establish IRE as the location for the research study to be documented in volume 2. In the following chapters, a study on self-directed learning is developed and the results are reported. Four findings of the work will be identified and presented.

This volume starts with theory and a review of literature. Self-directed learning (SDL) is defined and connected to other relevant cognitive learning processes. The previous works of educational researchers who have addressed self-directed learning and PBL are reviewed and conclusions are drawn. Self-determination theory (SDT) is introduced and described as the model to interpret factors that impact student motivation to learn. Finally, a main research question is developed and four sub-questions, whose answers will contribute to answering the main question, are created. Next, a chapter is dedicated to establishing the methodology for the qualitative study. The chapter starts with epistemological and theoretical positioning. Then a methodological decision-making is made visible, resulting in the selection of phenomenography as both methodology and method. Phenomenography is described and the steps of the qualitative method are described.

A mixed-method approach is used in this study. A quantitative comparison study is conducted with the intent to confirm the literature's prediction that a PBL education will result in development of self-directed learning abilities, whereas traditional engineering educations will not. This study is done at Iron Range Engineering with comparison groups at regional engineering universities. The intent is to study if there is a statistically significant development of SDL readiness for IRE graduates. The study confirms the expected results. This established the reason for a qualitative study to explore the characteristics of that development.

A qualitative study was conducted. 27 students were interviewed as a part of the phenomenography. Chapter 8 works through each of the phenomenography steps as the elements of self-directed learning used by the participants emerge, as do the processes they use to connect those elements. The outcome space of the phenomenography is presented in Chapter 9 as the different ways the PBL graduates view their self-directed learning. Further, a composite model of how the students experience SDL is developed and presented in Chapter 10. Quotes are used throughout the phenomenographic process, and then again as the results are confirmed through the theories presented in Chapters 2 and 5.

Volume 2 concludes with a summary of findings from the research study and a statement of the contributions to the state of the art.

CHAPTER 5. THEORETICAL PERSPECTIVE

5.1. INTRODUCTION

Engineering outcomes have been prevalent for the past two decades. Upon graduation from university, new engineers enter the field of practice expected to perform well across technical, design, and professional skill domains. While some of the knowledge necessary to succeed in these domains may have been acquired in their education, much of what they need will be acquired, as it is needed, in their new capacity. Further, the half-life of technical knowledge in the profession is often stated to be between 2-7 years (Wulf, 2002), meaning new learning will be a continual event throughout a 30-40 year career. I am the primary recruiter of new engineering students for the IRE program. During recruiting visits, I often engage potential students with this commentary:

> *"I'd like you to visualize your first day of work after graduation. Let me tell you two things that are not going to happen on that day… two things your new boss isn't going to say. First, she won't say "Greetings, John, welcome to ABC Engineering, we are glad you are here. I would like to introduce you to Dr. Jill. We have hired her to be your professor. When you need to learn something new, Dr. Jill will be here to teach it to you."*
>
> *The second thing she is not going to say is "Here are some textbooks. Each week, your job is to do the problems at the end of each chapter. If you get them correct, we will issue you a paycheck. At the end of each month, we will give you some written exams. Your performance on the written exams will determine the amount of your bonus."*

This story resonates with the students. To this point in their engineering education, nearly all of their learning has been one-directional from an instructor, and nearly all of their performance has been through the completion of closed-ended chapter problems and written exams. They know this is what they neither expect nor want as the duties in their profession. They struggle with this misalignment of activities during college, with expectations of experiences after college.

Lifelong learning, self-directed learning, self-regulated learning, and being metacognitive are all terms used, often interchangeably, to address the outcome expected of new graduates. The definitions, similarities, and differences will be addressed in a following section. However, a summary is that new engineering graduates are expected to be able to acquire new knowledge efficiently and effectively, and be able to use it to solve complex, ill-defined problems quite different than those at the end of a chapter in a textbook.

"Engineering practices are about knowing and using knowledge. The job of the engineer requires knowledge and the ability to utilize knowledge to solve real life problems…most engineers are constantly confronted with new problems and challenges where the engineer needs to acquire new knowledge." (Henriksen, 2001). The following quote from the International Engineering Alliance best communicates that the ability to learn could, arguably be the most essential of graduate outcomes:

> *"The fundamental purpose of engineering education is to build a knowledge base and attributes to enable the graduate to continue learning and to proceed to formative development that will develop the competencies required for independent practice." (International-Engineering-Alliance, June, 2013)*

Further, the following outcomes for engineering graduates from the Washington Accord at the international level, to the ABET criteria at the national level, to the IRE criteria at the program level, emphasize the importance of lifelong learning as an essential ability for new engineering graduates:

> *"Lifelong learning - Preparation for and depth of continuing learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change." (Washington-Accord, 2015)*

> *"A recognition of the need for, and an ability to engage in life-long learning" ABET Graduate Outcome L (ABET.org, 2015)*

> *Iron Range Engineering Performance Indicators for lifelong learning. "1) In a learning journal, demonstrate effective learning principles. 2) Develop and communicate personal learning model. 3) Apply metacognition techniques to improve individual learning." (Iron-Range-Engineering, 2016)*

Lifelong learning has multiple goals and fundamental principles (UNESCO Institute for Lifelong Learning, 2015, Medel-Añonuevo, Ohsako, & Mauch, 2001). Among them are "leading to the systematic acquisition, renewal, upgrading, and completion of knowledge, skills, and attitudes made necessary by the constantly changing conditions in which people now live" and "be dependent for its successful implementation on people's increasing ability and motivation to engage in self-directed learning activities" (Cropley, 1979). These descriptions focus on the importance of lifelong learning for engineers as they must be constantly acquiring, renewing, and upgrading their knowledge in their technical workplaces with themselves being the drivers to initiate and carry out the processes. Candy (1991) considers this relationship between lifelong learning and self-directed learning as being reciprocal with "self-directed learning (being) viewed simultaneously as a means and an end of lifelong education."

The evidence is clear; becoming a self-directed, life-long learner is an essential outcome for new engineering graduates to achieve.

This chapter builds on the importance, stated above, of developing lifelong learning abilities by following the line of thought that the essence of lifelong learning is the ability to self-direct and self-regulate one's own learning. Further proposed is that the development of these abilities is a function of the learning environment in which the engineering education is acquired. This chapter serves to provide the theoretical perspective under which the study, described and justified in the methodology (Chapter 6), is designed.

5.2. SELF-DIRECTED LEARNING

There are many terms that are used when describing the processes that are desired in, and used by, individuals when they acquire new knowledge. Metacognition, self-regulated learning (SRL), and self-directed learning (SDL) are among those terms most commonly used. An understanding of each, along with the commonalities and differences, is necessary in order to describe the development of the abilities in undergraduate students. Of further interest is the motivation that empowers the learner to initiate and continue as a self-directed learner. Self-determination theory (SDT) is addressed as a framework for interpreting these motivations. Each of the above are addressed in the following sub-sections.

5.2.1. METACOGNITION

In Chapter 2.4, there is an introduction to metacognition, a discussion on its importance, and a connection of metacognition to the APA principles of learning and Illeris' triangle. Now, in this section, metacognition is further defined so that it can be connected to the broader set of processes one uses in initiating and directing one's own learning. Flavell and Brown are often credited with bringing the concept of metacognition to the forefront (Tobias & Everson, 2009) through their writings of the late 1970s and early 1980s. As a term and an entity, mostly due to its complexity, metacognition itself is "fuzzy" and both hard to understand and to describe (Tarricone, 2011). Flavell's first written definition of metacognition in 1976 was " 'metacognition' refers to one's knowledge concerning one's own cognitive processes and products or anything related to them, e.g. the learning–relevant properties of information or data…Metacognition refers among other things, to the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects or data on which they bear, usually in service of some concrete goal or objective." (Flavell, 1976; Tarricone, 2011). Dissecting this quote, metacognition involves the following: knowledge, monitoring, regulation, and organization all in regards to learning goals. Another conception of metacognition is that it has two parts, metacognitive knowledge and metacognitive processes (Cornoldi, 2010). Where metacognitive knowledge is an understanding of how learning happens in both a general sense and a personal, individual sense (Wenden, 1998), metacognitive processes are actions taken such as self-monitoring, judgment, and regulation (Zimmerman, 2002).

Until 2011, the literature on metacognition is rather divergent. Many different authors offer views and sub-parts of metacognition without a coherent way to piece them all together. In 2011, Tarricone published "The Taxonomy of Metacognition"(Tarricone, 2011). It is a comprehensive model for breaking down metacognition into logical order. This framework allows the understanding of metacognition as the knowledge and set of actions that empower a person to learn. It is knowing how learning works by understanding the influences of the individual, the learning task, the learning strategy, and understanding the mechanisms that impact, monitor, and control learning. If learning is defined as memory acquisition, storage, retrieval and comprehension, then knowing about the person, about the tasks and strategies available and how to use them is essential. The act itself must be analyzed, monitored, and controlled (Tarricone, 2011).

The values of metacognition are that it is essential for learning (Tobias & Everson, 2009), it improves transfer of knowledge (Cornoldi, 2010), it improves problem solving (Cornoldi, 2010), and it improves quality and speed of learning (White, Frederiksen, & Collins, 2009). In general, people are naturally lacking in their use of metacognitive strategies (Winne & Nesbit, 2009). Fortunately, sophistication of metacognition can be taught (Desoete, 2009) and should be taught (Cornoldi, 2010; Serra & Metcalfe, 2009; White et al., 2009). Further, metacognitive abilities can be measured and monitored (Tobias & Everson, 2009). Metacognition is a central component in self-regulated learning (Winne & Nesbit, 2009).

5.2.2. SELF-REGULATED LEARNING

Zimmerman and Schunk are credited as being at the center of bringing self-regulated learning into the forefront of discussion (Alharbi, Henskens, & Hannaford, 2014; Nelson, Shell, Husman, Fishman, & Soh, 2015; Stolk, Martello, Somerville, & Geddes, 2010). In turn, Zimmerman and Schunk credit their work to the inspiration of Albert Bandura (Zimmerman & Schunk, 2011) and Paul Pintrich (Schunk, 2005). Research began to emerge on how people develop self-regulated academic learning in the 1980s (Zimmerman & Schunk, 2001). As with metacognition, there are many perspectives to consider when defining self-regulated learning (SRL).

In 1986, Zimmerman first defined SRL: “Students are self-regulated to the degree they are metacognitively, motivationally, and behaviorally participants in their own learning” (Zimmerman, 1986). A key to SRL is that the “learner displays personal initiative, perseverance, and adaptive skill” when pursuing her learning (Zimmerman, 2001). Further features of SRL include students’ “self-oriented feedback loops” and the students’ choices of learning processes, strategies, and responses (Zimmerman, 2001). Key components in SRL are planning, goal setting, strategy selection, environmental monitoring, help seeking, and maintaining a sense of self-efficacy (Zimmerman and Schunk, 2011).

Whereas metacognition covers all aspects of the person, tasks, and strategies from both the knowledge of and process using domains, self-regulated learning is more focused on using metacognitive aspects to excel, to become better at self-regulating one’s own learning. Self-regulated learners use metacognitive skills and knowledge to (Schunk and Zimmerman, 2008):

- Set better learning goals
- Plan to achieve goals through strategy selection
- Establish productive learning environments
- Implement strategies
- Monitor goal progress
- Adjust strategies
- Seek assistance when needed
- Expend effort
- Persist
- Evaluate
- Set new goals

Motivation serves as the impetus to start SRL, mediate SRL, impact the effectiveness of SRL, and is an outcome of SRL. The sources of motivation in self-regulated learning are these: self-perceptions of one’s own personal competence, mastery, and causal attribution, as well as outcome expectations, social environments, and the individuals value and interests (Schunk & Zimmerman, 2008).

The degree to which a person achieves his outcomes in SRL is largely dependent on how the person behaves and on his personal judgments of how well he will perform (Bandura, 1997). This interrelationship between people, their behavior, and their environment is the premise of Bandura’s social learning theory and is the foundation on which Zimmerman and Schunk’s models of self-regulated learning are built. Zimmerman and Moylan (2009) created a cyclical model for visualizing three phases of self-regulated learning. An adaptation of this model, used by Iron Range Engineering students in the design of their personal learning, is shown in Figure 5.1.

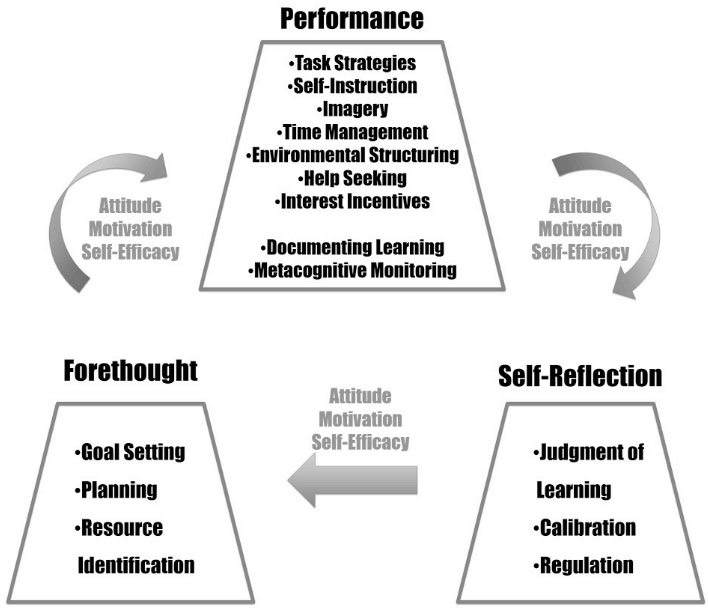

Figure 5.1. Three phases of self-regulated learning. Adapted from Zimmerman (Zimmerman & Moylan, 2009).

5.2.3. SELF-DIRECTED LEARNING

Carl Rogers has been revered as the "most influential psychotherapist in American history" (Rogers, Kirschenbaum, & Henderson, 1989). He pioneered a person-centered approach to counseling and therapy. His discoveries and methods transferred into other fields, such as health care and education. His early writings on education lay the groundwork for self-directed learning. In a presentation at Harvard in 1952, Rogers stated this view on learning: "I have come to feel that the only learning which significantly influences behavior is self-discovered, self-appropriated learning. Such self-discovered learning…cannot be directly communicated to another" (Rogers, 1958). Further, "The discipline necessary to reach the student's goal is a self-discipline and is recognized and accepted by the learner as being her own responsibility" (Rogers, 1975).

In the relevant research on self-directed learning (SDL) in engineering education, Candy's work (1991) is often cited (Jiusto & DiBiaso, 2006; Litzinger, Wise, & Lee, 2005; Stolk et al., 2010). Candy describes SDL as consisting of both product and process, each of which, he again subdivides. "Self-direction… refers to four distinct (but related) phenomena: 'self-direction' as a personal attribute (*personal autonomy*); 'self-direction' as the willingness and capacity to conduct one's own education (*self-management*); 'self-direction' as a mode of organizing instruction in formal settings (*learner control*); 'self-direction' as the individual, non-institutional pursuit of learning opportunities in the 'natural social setting' (*autodiaxy*)"(Candy, 1991). Figure 5.2 is a visual representation of Candy's four SDL phenomena.

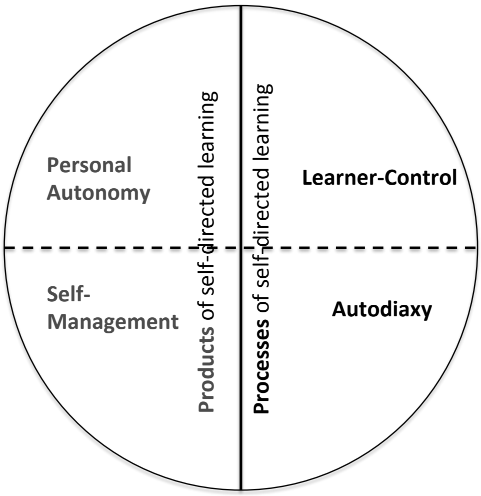

Figure 5.2. Candy's model of SDL

Personal autonomy and self-management would be the products of having attained some level of being a self-directed learner; whereas, learner control and autodiaxy would be processes of using self-directedness in learning in both formal and informal settings. If an outcome of engineering education is to have students ready to face the workplace as self-directed learners, it would seem desirable to have them acquire the attributes of personal autonomy and self-management, so that they can learn autodidactically in their engineering workplace.

The *processes* of self-directed learning (*learner-control and autodiaxy*) can be connected to the above-described concepts of metacognition and self-regulated learning. In *learner-control*, where the individual personally organizes and takes ownership of the learning in a formal environment, an instructor may make some of the decisions/actions in self-regulated learning for him. Examples could be that goals may be externally set, strategies may be dictated, or environments may be externally defined. From a metacognitive knowledge point of view, the individual will possess her own knowledge of the tasks and strategies and about herself as a learner. For metacognitive processes, the individual will monitor, control, judge, and regulate his learning actions. Contrasting *learner-control* to *autodiaxy*; in *autodiaxy*, the learner has full control and ownership of her self-regulated learning decisions and actions. Further, just as in *learner-control*, the individual possesses the metacognitive knowledge and controls the metacognitive actions. However, influencing metacognitive actions are the learner's metacognitive experiences and feelings. These experiences and feelings may be considerably different when in a learner control environment as compared to an autodidactic environment. In other words, the levels of autonomy, created by the differences between formal learning and informal learning, may directly impact the efficacy of the metacognitive actions taken by the learner. This concept is discussed in more detail in a future section on self-determination theory.

The *products* of self-directed learning (personal autonomy and self-management) can also be connected to self-regulated learning and metacognition. This connection is somewhat bi-directional, as the levels of autonomy and management will dictate the sophistication of the metacognition and the extents to which the learner will employ self-regulated learning actions in a given learning cycle. Conversely, the acts of using self-regulated learning and being metacognitive can impact the development of personal autonomy and self-management skill.

At the end of this chapter, the following research question will be developed:

"How do PBL students experience self-directed learning?"

Inserting the four subdivisions of self-directed learning from above, this question could be more specifically stated:

"How do PBL students in a *learner-control* environment, develop *personal autonomy* and *self-management* so that, upon becoming engineering professionals, they can learn *autodidactically?"*

Metacognition is the knowledge that the learner has about himself, the learning tasks, and strategies. The level of this knowledge impacts the levels of sophistication the learner can employ in organizing and achieving her own learning, whether in the *learner-control* formal settings or the *autodidactic* informal settings. Metacognition is also the set of processes the learner uses to organize, monitor, control, and regulate learning. The level to which the learner does this, is the level to which he *self-manages.* His level of *personal autonomy* directly impacts the levels of self-management. Self-regulated learning can be viewed as a process the self-directed learner uses to manage her learning. Inherent in the process are both the knowledge and action aspects of metacognition. The more advanced the learner the more advanced the processes. Completing the self-regulated learning cycle takes higher levels of initiative, personal autonomy, and the ability to manage the processes. To further compare and contrast, metacognition is both knowledge and process; self-regulated learning is process; self-directed learning is both process and attribute.

Summary - A self-directed learner possesses the personal autonomy and self-management attributes necessary to employ her metacognitive knowledge and metacognitive actions in a self-regulated learning process, while learning in either learner-control or autodiaxy environments.

5.3. SELF-DIRECTED LEARNING AND PBL

"The SDL emphasis is a distinguishing feature of PBL. In PBL, students become responsible for their own learning, which necessitates reflective, critical thinking about what is being learned (Bereiter & Scardamalia, 1989). In PBL, students are asked to put their knowledge to use and to be reflective and self-directed learners."
(Hmelo-Silver, 2004)

A major assumption of this PhD study is that there is interaction between PBL and SDL. The purpose of this section is to make that connection visible. Barrows and Kelson (1995) identify five goals behind the design of PBL instruction. Self-directed learning is explicitly stated. The goals are the following:

1) construct knowledge;
2) acquire problem-solving skills;
3) become self-directed learners;
4) develop effective collaborative skills; and
5) enhance intrinsic motivation to learn.

The act of engaging in SDL is an essential component of the student learning in PBL. Whether this is implicit for the students or made explicit by their facilitators, the students are involved in the practice of SDL when performing PBL. There are several elements of self-directed learning that are directly supported in project-based learning environments. They are the awareness of what they do/do not know, making learning goals, planning their learning, selecting strategies, monitoring goal attainment, and evaluating learning (Hmelo & Lin, 2000).

Other elements of learning addressed in detail in this thesis, which directly support SDL development, are reflection (Chapter 2) and motivation (Chapter 5.4). Hmelo-Silver (2004) summarizes research that suggests that more reflective learners demonstrate more advanced self-directed learning abilities. Further, attributes of PBL that make learning more meaningful to the individual and give her more control over her learning decisions lead to a more motivated learner.

To make the SDL/PBL interaction more explicit, the APA principles of learning, as described in Section 2.3, are used to seek commonalities and differences from SDL and PBL theory. Section 2.4 in volume 1 described PBL theory. Highlights from that section detail PBL as being constructivist, metacognitive, and socially contextual. The following principles of PBL (de Graaff & Kolmos, 2003) were described: the problem is the starting point of the learning process, learning is activity based, interdisciplinary learning happens in real situations, the majority of the learning processes take place in groups, learning is participant directed, and the goal of the learning is deep transferable knowledge. Further, Hmelo-Silver (2004) highlights intrinsic motivation as goal of PBL. As stated earlier in this chapter, SDL involves intentional process, goal setting, knowledge construction, strategic thinking, metacognitive action, and intrinsic motivation. These descriptions of PBL and SDL from theory translate to the APA principles listed in Table 5.1 below.

Table 5.1. PBL and SDL elements addressed in APA learner-centered principles of learning.

APA Principles Covered in PBL and SDL (from Section 2.3)		
	PBL	SDL
Nature of learning process	X	X
Goals of learning process	X	X
Construction of knowledge	X	X
Strategic thinking	X	X
Thinking about thinking	X	X
Context of learning	X	
Intrinsic motivation to learn	X	X
Social influences on learning	X	

This comparison finds alignment between PBL and SDL on the first five cognitive/metacognitive factors, as well as intrinsic motivation. Differences exist in that PBL theory supports context of learning, as well as the social factors.

As previously described, SDL readiness is a desired outcome of engineering education. Guglielmino (1977) further connects higher levels of SDL readiness with higher levels of problem solving ability and creativity. The above analysis leads to a conclusion that PBL curricula lead to development of SDL cognitive/metacognitive abilities. In the upcoming section, self-determination theory is presented. It provides a further discussion on impacts of motivation on learning; further connecting SDL and PBL.

5.4. SELF-DETERMINATION THEORY

PBL gives students more opportunities to have control over their own learning. This ownership creates increased motivation to learn (Bandura, 1997). In this section, Deci and Ryan's self-determination theory is presented. It connects this feature of control over one's own learning (autonomy) with the features of competence and relatedness.

Metacognition, self-regulated learning, and self-directed learning, as described above, represent the set of knowledge and actions taken by self-directed learners. Inherent in these concepts is a continuum of sophistication. At the low end of the continuum, the knowledge and actions are tacit and result in lower levels of learning. As the knowledge and actions become more explicit and intentional, the level of learning increases. An element needing further discussion is the role of motivation in causing the learner to start any phase of a learning cycle and impact the level to which the knowledge is accessed and the actions are executed. Self-regulated learning acknowledges that motivation is necessary to start any phase of the learning cycle. Schunk and Zimmerman (2008) identified personal attributes that impact motivation such as one's own personal competence and causal attribution. Self-determination theory provides a different framework for interpreting the impact of motivation on self-directed learning.

Deci and Ryan developed self-determination theory (SDT) in the 1980's (Ryan & Deci, 2000). SDT is an organismic theory from a Piagetian point of view, meaning that humans are naturally inclined to "elaborate their cognitive schema and representations of themselves and their world in a systematic and organized manner" (Deci, Ryan, & Guay, 2013). SDT is a "theory of motivation concerned with supporting our natural or intrinsic tendencies to behave in effective and healthy ways" (Self-Determination-Theory.org, 2015). Within SDT are 6 mini theories addressing the variety of topics from *intrinsic motivation* to relationships motivation (Self-Determination-Theory.org, 2015). The two mini-theories most applicable to self-directed learning are cognitive evaluation theory, which addresses *intrinsic motivation*, and organismic integration theory, which addresses *extrinsic motivation.*

These two mini-theories are based on three basic psychological needs: *competence*, *autonomy*, and *relatedness*. *Competence* refers to the belief that our learning actions are resulting in a gain of competence. Examples of learning actions that do not result in feelings of competence are actions that are perceived as either too easy (not worthy of time spent) or too hard (not achievable). Thus, optimal learning challenges can lead toward meeting the needs of competence, as can positive feedback and freedom from demeaning evaluations (Ryan & Deci, 2000). *Autonomy* in this context is where the learner perceives choice and opportunity for self-direction as being present in the learning environment. *Relatedness* is the feeling of belonging and connectedness in the learning environments. Self-determination theory holds that when these three basic needs are satisfied, self-motivation and well-being are enhanced. Whereas when they are inhibited, motivation and well-being are diminished. *Intrinsic motivation* occurs when the learner finds the topics interesting, challenging, and engaging. The levels to which these three basic psychological needs are met impact the levels of *intrinsic motivation*. When learners are more intrinsically motivated, they perform better, persist, and achieve higher levels of self-esteem, well-being, and interest (Ryan & Deci, 2000). However, *intrinsic motivation* to learn only happens when the only desired outcome is the learning itself. In other words, it happens when no external factors such as grades, degrees, career progression, etc. are present. These considerations make the motivations extrinsic.

To address *extrinsic motivation* in self-determination theory, Deci and Ryan established a continuum from highly controlled, externally regulated to highly autonomous, internally regulated (Ryan & Deci, 2000). The stages along the continuum are external regulation, introjected regulation (somewhat external), identified regulation (somewhat internal) and integrated regulation. The progression along the continuum aligns with the same three basic psychological needs of competence, autonomy, and relatedness. The higher the levels of support in the meeting of the needs, the further along the continuum the learner moves. Movement along the continuum results in similar increases in performance, persistence, interest, and well-being.

From self-determination theory comes valuable information on establishing and maintaining effective learning environments. Environments characterized as controlling, demeaning, impersonal, with external rewards and punishments would not align with developing motivations for learners to become personally autonomous and self-directed; whereas, these attributes and initiative are more likely to develop in environments that are supportive in these ways (Vansteenkiste, Lens, & Deci, 2006). Thus, when considering how PBL students develop as self-directed learners, self-determination theory can be used to explain how the PBL students' environments and perceptions of competence, autonomy, and relatedness impacted their development.

This positions self-determination theory as a further connector between PBL and SDL. PBL is highly dependent on the social interactions between group members. Thus, PBL learning environments provide many more opportunities for the psychological need of *relatedness* to be met. Further, PBL theory is dependent on participant-directed learning. When participants direct their learning, they are acting more *autonomously* than in lecture-directed learning. Higher levels of *relatedness* and *autonomy* mean more motivation, volition, and engagement. More motivation, volition, and engagement mean higher levels of performance, creativity, and persistence (Ryan & Deci, 2000), which mean higher levels of self-directed learning (Guglielmino & Guglielmino, 1977).

De Graaff and Kolmos (2003) report it is a "very common experience that students are more motivated and work much harder (in) the PBL model than (in) the traditional teaching model. Self-determination theory applied to the principles of PBL theory would predict this increased motivation and effort expenditure.

Self-determination theory would predict that students in PBL environments would have more opportunities to develop the motivation, volition, and engagement to achieve higher levels of self-directedness. In the next section, an instrument for measuring people's levels of self-directedness in their learning is presented.

In the SDL literature (Hmelo-Silver, 2004; Stolk et al., 2010), the role of autonomy afforded in PBL is directly connected to increases in motivation and performance, as would be predicted by SDT. (Stolk, et. al. make a direct link). An important attribute of PBL curricula is the team environment and the intimate role played by the facilitator (de Graaff & Kolmos, 2003; Du, de Graaff, & Kolmos, 2009; Kolmos, 2007). From Section 5.3 above, developing collaborative skills is a primary goal of PBL (Barrows & Kelson, 1995). This community aspect of PBL environments has the potential to lead to higher levels of motivation leading to higher levels of performance in self-directed learning.

5.5. SDLRS

L. Guglielmino originally wrote the Self-Directed Learning Readiness Scale (SDLRS) in 1977 (Guglielmino, 1977). In order to develop the instrument, Guglielmino performed a Delphi study (Guglielmino, 1977), wherein a panel of experts in the field was surveyed in order to determine the essential attributes of highly self-directed learners. The study resulted in the following definition:

> *"A highly self-directed learner, based on the survey results, is one who exhibits initiative (SDL), independence, and persistence (SDT) in*

learning; one who accepts responsibility (SDT) for his or her own learning and views problems as challenges (PBL, SDT), not obstacles; one who is capable of self-discipline and has a high degree of curiosity; one who has a strong desire to learn or change and is self-confident; one who is able to use basic study skills, organize his or her time and set an appropriate pace for learning, and to develop a plan for completing work; one who enjoys learning and has a tendency to be goal-oriented."(Guglielmino & Guglielmino, 1977)

Guglielmino used this definition to create the SDLRS instrument. Over 120,000 adults have since taken the instrument. Further information about the instrument, as well as its attributes, reliability, and validity are presented in Chapter 7.

In the previous section, self-determination theory was used to predict that learning in PBL curricula could result in higher levels of self-directed learning development. In this section, a method for measuring SDL ability has been identified. In the next section, several research studies from the literature are presented. These studies use the SDLRS to measure development in students in PBL vs. traditional learning environments. The theories presented above would predict higher levels of performance in PBL.

5.6. PREVIOUS WORKS IN ENGINEERING EDUCATION

A comprehensive review of the literature reinforces that self-directed learning has emerged as a critical component in the graduate outcome of lifelong learning. When studied quantitatively, PBL learning environments have shown to increase SDL abilities, while traditional learning environments have not. Common throughout most studies of SDL is the use of Guglielmino's (1977) SDLRS instrument to measure self-directed learning readiness. Many of the findings and recommendations that have emerged from these studies align with the self-determination theory presented in the previous section. Further, while there have been studies on the existence of self-directed learning development in PBL learning environments, the focus has been on identifying that the SDL abilities are developed, and little has been studied about *how* the abilities are being developed.

5.6.1. VALUE OF SELF-DIRECTED LEARNING

The importance of lifelong learning for engineering graduates has been highlighted for decades. Shuman, Besterfield-Sacre, and McGourty in their often referenced Journal of Engineering Education article (Shuman, Besterfield‐Sacre, & McGourty, 2005) on ABET professional skills demonstrate a focus on this outcome that dates back to 1968. In the same article, they reference Litzinger and his colleagues who are "at the frontier of studying lifelong learning relative to engineering education." Now, 10 years later, in an email dated January 2015, Litzinger commented:

> *"The work in JEE was the end of a project that we conducted. We did not (do) additional work. I am aware of only one other study related to SDL. It was done by David DiBiasio at WPI and appeared in JEE: Experiential Learning Environments: Do They Prepare Our Students to be Self-Directed, Life-Long Learners? Volume 95, Issue 3, pages 195–204, July 2006. I agree with your assessment that there has been very little work on SDL or SRL in engineering education." (T. A. Litzinger, 2015)*

Further review of literature bears out Litzinger's comment. There is little published work on the impact of the development of engineering graduates to be prepared to acquire technical knowledge beyond graduation. Further, the works that do exist are not conclusive.

Shuman et al. (2005) identified the specific attributes of lifelong learning as: "demonstrating reading, writing, listening, and speaking skills; demonstrating an awareness of what needs to be learned; following a learning plan; identifying, retrieving, and organizing information; understanding and remembering new information; demonstrating critical thinking skills; and reflecting on one's own understanding." They went on to propose that these attributes are acquired as a result of simply becoming proficient in the other ABET outcomes. "Hence, one will become a proficient lifelong learner as one becomes proficient in the broad spectrum of professional skills." (Shuman et al., 2005) This implies that the implicit learning, as opposed to explicit learning, of lifelong learning skills is adequate in developing proficiency. The results of studies of traditional engineering student acquisition of SDL readiness strongly oppose this view.

5.6.2. SELF-DIRECTED LEARNING IN TRADITIONAL ENGINEERING CURRICULA

Litzinger et al. (2003) used Guglielmino's (1977) Self-Directed Learning Readiness Scale (SDLRS). Using 400, randomly selected, engineering students across semesters 1-8 in the bachelor's program, this research group sought to identify differences in self-directed learning readiness across students in the different levels of their education and also between genders. "…there were no statistically significant changes in average SDLRS scores among students in first through eighth semesters… The study did not show any significant differences between male and female students." A follow-up study of 600 students was performed, this time extending to students in semesters 9 and 10. Again, there were no significant increases in SDLRS. In 2005, Litzinger et al. (2005) published a study, from the same original data, in the Journal of Engineering Education, by this time, they had discovered, a weak correlation between year of study and SDLRS score. Yet they still concluded, "that academic year is a poor predictor of SDLRS score."

5.6.3. PBL IMPACT ON SELF-DIRECTED LEARNING

Included in the study of 1000 traditional engineering students, Litzinger et al. investigated the effect of PBL on SDLRS scores by having 18 third year engineering students complete the SDLRS assessment pre- and post- of a two-semester PBL sequence. "The average pre-test score was 216…the average post-test score was 227. The difference between them was shown to be statistically significant and the research team concluded, "the problem based learning approach used in IME, Inc. (the PBL program) was effective in increasing the SDLRS scores of the students" (Litzinger et al., 2005).

In 2006, Jiusto and DiBiaso published "Experiential Learning Environments: Do They Prepare Our Students to be Self-Directed, Lifelong Learners"(Jiusto & DiBiaso, 2006). In this article, the authors relate the emerging focus on lifelong learning with the publication of the ABET 2000 criteria in the late 1990's. They also cite Litzinger's work showing that traditional engineering programs seem to have no effect on increasing students' capabilities for self-directed learning. The focus of their work was to determine the impact of experiential learning environments on students' self-directed abilities. They used triangulation from the SDLRS, another self-report instrument called IDEA, and faculty review of project reports. 259 students took the pre-test, 198 students took the post-test, 138 student samples were paired pre- to post-. There were no statistical differences between the paired vs. total sample results. The SDLRS scores increased from 219 (pre) to 222 (post), which was shown to be statistically significant ($p=0.06$). The conclusions of their study, when incorporating the other two methods, were that the experiential learning experience did result in slight improvements in lifelong learning capabilities. They noted some instances where the capabilities decreased pre- to post. Examples were students who had initially high SDL capabilities before the experience and students whose experience happened to be in a non-English speaking environment.

A 2007 study published in EJEE related incoming readiness for SDL and ability to achieve outcomes in PBL. The case study analyzed international students in a master's course in engineering management in Australia. The hypothesis was that higher indications of SDL readiness in incoming students would gain greater learning outcomes in a PBL environment (Stewart, 2007). In tool selection, Guglielmino's (1977) SDLRS was chosen for its proven accuracy. In addition to using the total score as was used by Litzinger and Jiusto, subscales were used. They are self-management, desire for learning, and self-control. There were 26 individual respondents. A regression analysis was used to correlate initial SDLRS scores with learning outcome values. All subscales and the overall score showed a positive correlation with learning outcome attained. Self-management (LO= .72(SM) +1.17, R^2 = .50) and overall SDLRS (LO= .73(SDLRS) +.97, R^2 = .40) showed the most positive indication (Stewart, 2007).

5.6.4. OTHER RECENT RESEARCH RELATED TO SELF-DIRECTED LEARNING

Stolk et al. (2010) created a framework for self-directed learning based on the literature from self-regulation and adult learning literature. They used the framework to study students' conceptions of SDL. Using the entire student body from Olin College, 295 mechanical, electrical/computer, and general engineering students, the instrument was a 5-point Likert quantitative survey with three additional short-answer questions. 197 students completed the survey, with 159 completing the short-answer questions. There was gender balance in the respondents, as well as balance across the four academic years. Olin College uses PBL across its curriculum. The three short-answer questions were: 1) Provide a definition of self-directed learning, 2) List the features of self-directed learning that you think make it effective, and 3) List the features of self-directed learning that you think make it challenging. Figure 5.3 below shows the distribution of responses in the SDL framework.

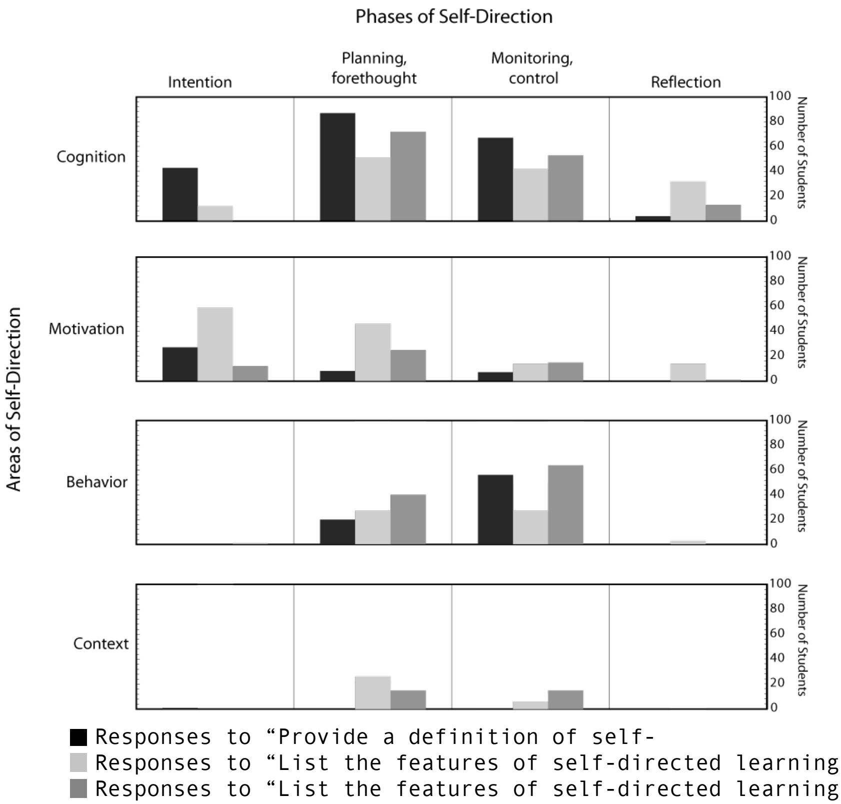

Figure 5.3. Results from coding student short-answer responses to SDL framework. (used with permission) (Stolk et al., 2010)

As can be seen in the results, students paid little attention to both reflection (right column) and context (bottom row) in their responses. The most frequently mentioned area of self-direction was cognition, and the most frequently mentioned phases of self-direction were planning/forethought and monitoring/control. The research group used their conclusions to make three recommendations for implementation in curriculum design: 1) consider ways to give students control, 2) include self-reflection assignments in all courses, 3) provide appropriate scaffolding for SDL skill building. These recommendations align with the self-determination theory considerations of autonomy, competence, and connectedness. Further conclusions were that motivational aspects were frequently mentioned as positive outcomes of SDL and behavioral aspects, such as time management, were most frequently noted as the negative attributes of SDL. One of the areas of suggested future work for this study was student reflection in SDL (Stolk et al., 2010).

In another study investigating SDL and PBL, the researchers connect the importance of self-reflective abilities in the development of SDL capacity and then use grounded-theory to analyze how students develop SDL abilities in the first two years of an engineering curriculum (Burger et al., 2014). The study included subjects from both a large traditional engineering program and a small PBL program. The results of the work identified the following barriers to self-reflective development: 1) lack of freedom within course content, 2) perceived poor performance on traditional assessments, 3) lack of agency developed in traditional classrooms. The primary conclusion from the study is that “environments with high levels of cognitive autonomy, as well as non-traditional learning environments, seem to develop deeper reflective practices” (Burger et al., 2014). A further conclusion is that teaching faculty can use *reflection* after students encounter challenges to empower students to acquire more sophisticated learning strategies.

In a different PBL vs. non-PBL study at Olin College and California Polytechnic State University at San Luis Obispo, self-directed learning capabilities were studied in first year engineering students longitudinally over the first two years of their education (Stolk & Harari, 2014). Approximately 50 students were studied using quantitative and qualitative methods. The quantitative results are published in this study. The qualitative results are, as of yet, unpublished. The quantitative measures were used to study academic motivations, goal orientations, conceptions of learning, metacognitive knowledge, and metacognitive strategy use. Results highlighted similarities and differences between PBL students and traditional students. In academic motivations, traditional students were significantly different from PBL students in their higher levels of external regulation. In goal orientations, both groups reported high learning orientation vs. grade orientation. However, the PBL students reported significantly higher levels of learning orientation attitudes, behaviors, positive regard for instructors, and negative regards for easy, irrelevant learning. The entering students at both institutions were similar with regards to conceptions of learning with the exception that the PBL students showed a higher regard for peer learning. At the end of the two years, this higher regard for peer learning remained and an additional attribute of a higher regard for knowledge construction emerged. Further, at the end of the second year of learning, students in both groups had “not completely embraced self-direction and were not yet confident in their ability to learn without an instructors guidance and evaluation” (Stolk & Harari, 2014). With regards to metacognitive awareness, both groups entered college at similar levels and left after two years with no recognizable development. Two conclusions of the work are that there are measurable differences between the PBL students and traditional students (from both the perspective of those who chose to enter each model, as well as by the developments within the model) and that students’ SDL abilities remained stable across the two years of their engineering study, with a further notice that gains that arose during year 1 of education disappeared by the end of year 2.

Bary and Rees (2006) in the European Journal of Engineering Education, used a research project to connect self-directed learning to innovation. They identified three main aspects of SDL used by innovators: self-information, experiential learning, and learning with/from others. From these results, they concluded that "learning to become self-directed learners" should be integrated into engineering curricula. They designed and implemented curricular integrations. Interestingly, they inserted them into the English learning component of the curriculum, rather than the science and engineering components. This was done since it was determined the science/engineering faculty lacked the "psychopedagogical background" to "radically break from their pedagogical practices" (Bary & Rees, 2006). The curricular integration was implemented in each of the three years of the engineering bachelor's with different aspects of SDL skills being learned in each of the years. By the publication date of the journal, four years of implementation were underway. They had not used any standard measures of SDL nor developed their own measure and considered this the main weakness of their project. Further literature review is not able to identify any published results since this article.

In 2006, in the European Journal of Engineering, Guest (2006) addressed the importance of lifelong learning for engineers from a global perspective. No research was reported, only a call for important focus. He detailed attributes of fully effective adult learners, including the ability to "…conduct research into elements of professional knowledge, practice and competence that lie within the context of their work, in pursuit of solutions to "problems of the day", personal professional development, and (more generally) the development of their profession"(Guest, 2006). Further, Guest looked towards the future identifying several ideas, including "all learning will be lifelong learning and include continuing professional development. It will be our own individual responsibility, as self-directed learners, but undertaken with help, support, and guidance from our coaches, mentors, colleagues, and fellow networkers." And "we will become more proficient at learning how to learn, accessing new information and seeking out new sources of knowledge using information and communication technologies." (Guest, 2006).

There are a few other recent articles in the literature that address self-directed learning. However, it is in a tangential way rather than directly analyzing student development of SDL capabilities. Reich (Reich et al., 2014) in the European Journal of Engineering Education relate professional learning of the engineer to the greater social environment in which the engineer finds himself in practice, rather than basing it solely on his individual abilities. Wertz (Wertz, Purzer, Fosmire, & Cardella, 2013), in JEE, drew connections from lifelong learning to information literacy, calling it a critical component of lifelong learning. Citing the recent literature that show, lifelong learning skills are highly valued by employers and traditional engineering education does little to improve such skills, the authors concluded that engineering students have weak information literacy skills. DiDomenico, in a paper to the Conference for Industry and Education Collaboration for the American Society of Engineering Education (2010), summarized the works of Litzinger and Jiusto discussed above, provided evidence that self-directed learning skills are essential in engineering education, and stated that the teaching of SDL skills should be incorporated directly into the curriculums (DiDomenico, 2010). Finally, in January 2015, in JEE, Nelson et al. published the results of a study analyzing the motivational and self-regulated learning profiles of engineering students in foundational courses. Using a tool, they developed and validated, the Student Perceptions of Classroom Knowledge Building scale (SPOCK), they concluded that students only adopt positive motivational and self-regulatory attributes when they both perceive the course as useful for their engineering future and perceive that they have control over their learning. When either of these is missing the students adopt "maladaptive goal orientation… and lack effective self-regulatory learning behaviors"(Nelson et al., 2015).

5.6.5. PREVIOUS WORKS CONCLUSIONS

Following are conclusions drawn from the above research:

1. Foremost is that self-directed learning has become a highly valued outcome of engineering education (Stolk 2014, Burger 2014, Reich 2014, Wertz 2013, Didomenico 2010, Stolk 2010, Stewart 2007, Bary 2006, Guest 2006, Litzinger 2005, Litzinger 2003).

2. There is a pattern of quantitative research indicating that a traditional engineering education results in little, if any, development of self-directed learning abilities (Litzinger 2003, Litzinger 2005, Wertz 2013, Stolk 2014).

3. Further, there is a pattern of research that indicates project-based learning can result in SDL development (Litzinger 2005, Jiusto 2006, Stewart 2007, Burger 2014).

4. Guglielmino's self-directed learning readiness scale (SDLRS) has been validated and widely used to measure self-directed learning readiness (Litzinger 2003, Litzinger 2005, Jiusto 2006, Stewart 2007, Wertz 2013). SDLRS results need not be paired pre- to post- to be valid (Jiusto & Diabiaso, 2006). The SDLRS can be used to predict success in PBL (Stewart, 2007).

5. Explicit self-directed learning skill acquisition and scaffolding should be included in the curriculum (Guest 2006, DiDomenico 2010, Burger 2014). Student ownership in choice during instruction is key to the motivational aspect of SDL (Burger 2014, Stolk 2014, Nelson 2015). The basic psychological needs of competence, autonomy, and connectedness as identified by Deci and Ryan's self-determination theory can commonly be connected to the outcomes of this current research.

6. Considering the importance, little work has been done to understand *how* engineering students develop as self-directed learners (Stolk et al., 2014).

7. Nearly all works reported in the literature on self-directed learning are quantitative in nature, whereas qualitative approaches have promise (Stolk & Martello, 2015).

5.7. CONCLUSIONS FROM THE LITERATURE

By understanding the relationships between PBL education and the development of self-directed learning abilities in one PBL context, engineering faculty in other PBL programs or non-PBL programs could be prompted to think about how their engineering students develop these abilities. To understand self-directed learning in a greater context, lifelong learning, metacognition, self-regulated learning, and self-determination theory have been synthesized to show how each contributes to the development of SDL in engineering students. Recent relevant literature has been presented. Themes relevant to this PhD work have emerged from this theoretical perspective: 1) SDL development is important for the engineering student to succeed after graduation; 2) PBL, from its pedagogical perspectives, is well-positioned to lead to SDL development of students; recent research confirms that it can; 3) there is a validated scale that can be used to analyze SDL development.

While there is research showing *that* PBL students can and do develop SDL abilities, there is little information on *how* this development occurs.

5.8. RESEARCH QUESTION DEVELOPMENT

From the motivations to study self-directed learning development in PBL students, came the main objective of the study, which is to create knowledge for future engineering education decision-makers to consider when making curricular decisions. In this chapter, self-directed learning has been defined and positioned with respect to learning elements and with respect to works in the literature. In an effort to meet the objective, the following research question has emerged:

"How do PBL students experience self-directed learning?"

Four sub-questions, listed below, when answered will result in answers for the main question. The sub-questions are as follows:

1. How do PBL students develop compared to non-PBL students?

2. What are the different elements of self-directed learning that students experience and to what level do all students experience the variety of elements?
3. What are the different ways PBL students view self-directed learning?
4. How does PBL student development of SDL abilities align with theory?

Sub-question 1 should be answered first. The hypothesis is that they develop more self-directed attributes than non-PBL, traditional students. This hypothesis comes directly from the literature in the previous section.

CHAPTER 6. METHODOLOGY

The purpose of this methodology chapter is to describe the research tools and approaches used in this study while justifying the theoretical structure in which the methods exist. The previous chapter has provided the theoretical underpinnings of self-directed learning and its connections to engineering education. This chapter justifies how it will be studied.

6.1. RESEARCH QUESTION AND MOTIVATIONS

"How do PBL students experience self-directed learning?"

In Chapter 5, a deep justification for the study of this topic is grounded by the literature. In summary, the concept of lifelong learning is expected as an outcome for new engineering graduates. This outcome is interpreted to include the ability of the new engineer to start, direct, and regulate her own learning through the use of metacognitive skill and strategy.

When the engineering classroom focus is on the content of learning, and not on the processes, students leave courses with a short-term understanding of material acquired through processes that are unlikely to result in transfer to future problem solving situations (Fink, 2013). Changing the focus to the process of learning, specifically, acquiring and using metacognitive and self-directed learning skills brought with it the potential for students to gain longer-term value from their learning (Ambrose, Bridges, DiPietro, Lovett, & Norman, 2010). The work of developing and implementing a PBL engineering program and the learning acquired in this PhD study, combined with the apparent lack of focus on the development of SDL skills in engineering programs world-wide (see Section 5.6), leaves a feeling of obligation to undertake this study and share the results widely. Decision makers in engineering departments can be inspired to look at how students in their programs develop self-directed learning abilities and, perhaps, put more focus on the development of those abilities.

6.2. THEORETICAL STANCES

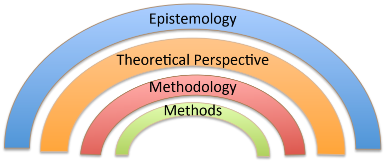

Figure 6.1. Theoretical stances.

Crotty (1998) describes a hierarchy of the elements in any research process. The first element is the epistemology, which is a belief system about what is known and how it can be known. The next element is the theoretical perspective, which informs the methodology through a philosophical bearing. Methodology is then considered to be the design of methods selection and implementation, as influenced by the epistemology and theoretical perspective. Finally, the methods are the instruments and procedures used to collect and analyze the data. Case and Light in the Journal of Engineering Education (Case & Light, 2011) note that many "methodology" chapters in PhD dissertations are only a listing of the methods used and do not provide the theoretical and philosophical justifications behind the research. Borrego and Douglas, also in the Journal of Engineering Education (2009), argue the necessity of including all four elements as the lens through which the findings can be interpreted. The two aforementioned JEE articles, along with a third by Baillie and Douglas (2014), are written in an attempt to bring credibility and acceptance of qualitative research to the engineering education community, which has been traditionally aligned with objectivist, positivist, quantitative philosophies and methodologies. This proposed acceptance of the qualitative philosophies and methodologies provides both an assurance and guidance for the works of this research. Following are descriptions of the epistemological, theoretical, and methodological choices for this research, along with alternatives considered and justifications for decisions.

6.2.1. EPISTEMOLOGY

The epistemological stances and perspectives tend to be described on a continuum from objectivism on one end of the spectrum to constructionism on the other end (Crotty, 2003). On the objectivism end, there is but one factual reality, and hard objective data is used to find it. Toward constructionism, there are multiple realities dependent on the situation and the experiences of the people involved. In Chapter 2 of this work, curriculum and learning theories were discussed as they apply to the underpinnings of PBL, of the curriculum designed at Iron Range Engineering, and to the emerging views on how people learn. All of those discussions lead to social constructionism. This can also be seen in the works of Bransford and the learner-centered principles of learning by the American Psychological Association (2014). Further, Kolmos and de Graaff, in the recent

Cambridge Handbook of Engineering Education (2014) explicitly state, as they have in many publications in the past (de Graaff & Kolmos, 2007; Du et al., 2009; Edström & Kolmos, 2014) that “PBL practice is a social construction.” It would seem just then, that the epistemological stance for this current research should align with constructionism.

The tendency towards objectivism does, however, exist. Engineers tend towards being quantitative rather than qualitative. They want statistical significance leading toward an indication of cause and effect, or absolute truth. Engineering education, as seen through the lens of articles published in the Journal of Engineering Education follows suit (Case & Light, 2003; Borrego & Douglas, 2009; Baillie & Douglas, 2014).

I come from two backgrounds: one, as a traditionally trained, licensed professional engineer who has practiced in a military industrial environment; the other as an educator who has taught for more than 25 years, observing closely the complexities of how people learn in a wide variety of situations. This dichotomy of backgrounds leads to a tension in epistemological beliefs. Prior to the learning accomplished during my PhD studies, this tension would have pulled much harder towards the absolute of objectivism. However, having gained a deeper perspective of constructionism and reflecting on years of educational practice, as well as daily classroom interactions, my epistemological beliefs are found firmly rooted in constructionism. Despite these beliefs, my practice in this PhD does reflect some quantitative, objectivist actions, particularly in the Chapter 7 quantitative study. In the qualitative study, I have attempted to design and interpret through a constructionist philosophical lens.

6.2.2. THEORETICAL PERSPECTIVE

As with epistemology, theoretical perspective has a continuum with, on one end, a cause and effect, searching for a single reality, often deemed positivist/post-positivist. While on the other end, multiple realities exist taking into account the specific situations. Here, an interpretivist approach seems to take meaning from the experiences of the people involved (Case & Light, 2011). Thus, a positivist theoretical perspective would be more aligned with an objectivist epistemology and similarly, interpretivism would be more aligned with a constructionist epistemology. As stated previously, a major goal of this research is to describe the development of self-directed learning for the specific student experiences in the specific situation at Iron Range Engineering and characterize these experiences. Others may consider how this knowledge may be useful in their specific curricula with their specific learning environments. This work is considering multiple subjective realities. It is interpreting the experiences of students in one specific social construct. The researcher is not detached from the learning situation, but could be considered a partner with the students in the experience. The flexibility of the methods is considered to be reactive to knowledge gained during the process. Finally, the outcome of this research is desired to be situated descriptions of how, and how well, the PBL students develop self-directed abilities. Thus, this research study is being undertaken from an interpretivist, situational, theoretical perspective. The choice is aligned with the epistemology and is consistent with the pedagogy, as well as this researcher's philosophical stances; all stated in the previous section.

6.3. METHODOLOGY

The methodology is the combination of the epistemological and theoretical perspective elements and the description of the methods approach. The epistemology and theoretical perspectives, described in the previous section, drive the methodological decisions and construct, which will lead to the methods used to collect and analyze data in this study.

A mixed-methods sequential explanatory design (Creswell, 2013) was undertaken for this study. Using further mixed-methods notation from Creswell (Creswell & Clark, 2007), the study is quan -> QUAL, annotating the quantitative study as minor in scope as compared to the qualitative study. The first part of the study consists of quantitative research, comparing PBL graduates to non-PBL graduates, in their development of self-directed learning abilities during their engineering education. As highlighted in Chapter 5, research has indicated that students undergo development in SDL abilities during PBL instruction; whereas development has not been associated with non-PBL instruction. Part one (Chapter 7) of this study aims to confirm those results by analyzing the Iron Range Engineering PBL graduates, to identify if there is significant SDL development, as well as to analyze a comparison group of non-PBL participants, to identify if there is no development. Part two (Chapters 8, 9, & 10) of this study is a qualitative study of the PBL participants explaining the PBL development by analyzing how the PBL students experience self-directed learning.

Quantitative data collection took place from 2011 to 2015. Quantitative analysis preceded the qualitative design and implementation. The results of the quantitative analysis were used to determine the need for and direction of the qualitative study. Thus making the study both sequential and explanatory (Creswell, 2013).

Case and Light (2011) propose that there are many emerging qualitative methodologies that show promise for use in engineering education research. Their list of emerging methodologies include case study, grounded theory, ethnography, action research, phenomenography, discourse analysis, and narrative analysis. Crotty (1998) includes experimental research, survey research, ethnography, phenomenological research, grounded theory, heuristic inquiry, action research, discourse analysis, and feminist standpoint research. While this list is not exhaustive, it does provide a base set of methodological options to consider for situational, interpretivist research.

6.3.1. CURRENT RESEARCH SITUATION

The methodological choices for this study needed to align with the epistemological and theoretical perspectives, as well as the particular research situation in place. To better justify methodological choice, a description of the particular research situation follows.

I was the principal investigator on two studies relevant to the PhD research since 2011, two years prior to the start of the PhD program. “Study A” looked at the professional, technical, and cognitive development of PBL students as compared to non-PBL students. Survey research using validated and newly created tools, concept inventories, and an interview protocol, developed and implemented by co-PIs at the University of Minnesota, determined the methods for this study. “Study B” analyzed the development of problem solving ability, identity, and metacognitive skills of PBL students vs. non-PBL students, and was done in conjunction with co-PIs at the University of Missouri. The most pertinent data to this study is a validated tool from educational psychology, the SDLRS (Guglielmino, 1978). Initial data is available for pre- and post- education for both IRE PBL and non-PBL groups. Throughout the duration of the PhD study, SDLRS data continued to be collected.

The groups being studied include the students in the four-semester IRE program. Each semester, 5-15 new students start and a similar number graduate. At any time, there were 50 students in this PBL program, progressing from new 3rd year students to 4th year second semester students graduating with bachelor’s degrees. Two comparison groups used in the above-mentioned studies include students who had a similar first two-year preparation at a local community college and then transferred to a non-PBL university to complete their engineering degree, as well as students who started and completed at non-PBL universities.

The final aspect to be considered about the current research situation was the position that I had with regard to the research and the students. I am an integral daily part of the student experience in the IRE PBL program. I am the director and “culture-keeper” of the program. I teach a weekly professionalism seminar class to every student in the program, with topics that range from ethics to communication to learning about learning. I facilitate one project team per semester, and teach some of the core technical material to the students. This level of interaction with the students, while being a researcher on the program, needs to be addressed from the perspectives of the potential benefits it adds, the potential disadvantages, the biases that need to be addressed, and the perceptions of validity of the results.

These considerations of current research being conducted, student groups, and placement of the researcher within the study all contributed to the methodological choices made about the research design.

6.3.2. METHODOLOGICAL OPTIONS

Table 6.1 lists the methodological choices described by Case and Light (2011) and Crotty (1998) and includes qualitative methodologies listed in the Sage Encyclopedia of Social Science Research Methods (Lewis-Beck, Bryman, & Liao, 2003).

Table 6.1. Methodological options

Methodology	**Statement of Applicability**
Grounded theory[1]	Grounded theory is beyond the scope of this work. New theories of how people acquire self-directed learning abilities are not the intent.
Ethnography[1]	An ethnographic methodology is not aligned with the goals of this research. Ethnography would be looking at the characteristics of the IRE culture and the people being studied.
Action research[1,3]	The dual focus does exist. The researcher is motivated to both answer the research question and use the research results to improve the approaches used for student acquisition of SDL abilities. This study is done by one of the program's practitioners.
Phenomenography[1,2]	Phenomenography would result in a characterization of how the students experience SDL . The outcome would be a collection of descriptions of the different ways the students experience SDL. Data collection could be through normal qualitative methods such as interviews.
Case study[1]	The experiences of the PBL students on which a qualitative study can be performed will be the analysis of a single case of a phenomenon. The case will be set in a specific, unique circumstance. The intent would be to richly describe and discuss the results presenting them in a way that would allow others to use this case to analyze similarities and differences to their own situations and use these

	results to prompt action.
Discourse analysis[1]	Discourse analysis could be used in this study. However, by itself, without other more direct interactions, discourse analysis wouldn't get to the specific details of the SDL framework.
Experimental research[4]	Experimental research counters the epistemological and theoretical perspectives arrived at in sections above. However, there is much experimental research data available through the research grants being conducted for the NSF on this topic in this program. This method will be used in quantitative study.
Phenomenological research[2]	Phenomenology aligns with a goal of this research, which is to understand the acquisition of SDL abilities by PBL students. The outcome would be a description of how this group of students experienced their development as self-directed learners, as determined by the commonalities in their experiences as gathered from their first person points of view. Phenomenology may be used to interpret findings.
Heuristic inquiry[2]	In this model, the researcher would be the center of the research. This is not the goal of this work.
Design-based research[3]	Using a design-based research approach would have been an excellent choice if this study had been undertaken earlier in the development of the IRE model. By the time this study was undertaken, the curriculum had reached a point where cycles of continuous improvement are more applicable than is new design.

[1](Case & Light, 2011)
[2](Lewis-Beck et al., 2003)
[3](Sandoval & Bell, 2004)
[4](Sullivan, 2009)

A quick recap of the above list shows that five of the ten methodologies considered were eliminated due to misalignment with this work:

~~grounded theory~~	~~discourse analysis~~
~~ethnography~~	experimental research
action research	phenomenology
phenomenography	~~heuristic inquiry~~
case study	~~design based research~~

The constraints applied to the decision of methodology for the qualitative study as described in preceding sections are the following: 1) to perform the study from a constructionist epistemology, 2) to take an interpretive, situational theoretical perspective, 3) to perform the study on a group of Iron Range Engineering students, and 4) for this researcher, an integral academic staff member in the IRE program, to perform the research. These constraints dictate that the study is a case study (constraint 3) and that this is action research (constraint 4). Constraints 1 and 2 provide the lens through which the work was undertaken and interpreted.

The existence of experimental research, which began in 2011, and was ongoing, entered into the methodological decision-making. The first decision was whether to use it? The answer to the first decision was yes, since the existence of the data was compelling and a motivation to begin the PhD study. The second decision became how to use it? There are quantitative measures that can indicate development of self-directed learning abilities and some of these tools have been applied at Iron Range Engineering, with the groups that were studied when answering the research question. Thus, since the answer to question 1 was yes. The answer to question 2 leads towards a mixed-methods approach. Creswell defines mixed methods as "The 'mixing' or blending of data…providing a stronger understanding of the problem or question than either (quantitative or qualitative) by itself." (Creswell, 2013). The preliminary and ongoing experimental data justified the need to explain the results using a qualitative approach.

Further methodological decisions were to be made. While some methodologies had been evaluated and dismissed, decisions have been made to embrace case-based, action research, with input from experimental research results. However, the approach for the action research can still be refined. From Table 6.1, the two remaining methodologies to be evaluated for the qualitative study were phenomenography and phenomenology. The similarities were that both fit the constructionist epistemology, the interpretivist and situational theoretical perspective, the case-based approach, and can be used in action research. There are, however, major differences. Phenomenology is focused on the phenomenon itself, whereas phenomenography is focused on the experience of the phenomenon (Limberg, 2008). Phenomenology seeks to describe the experiences of the group of people, as derived from the common themes in their first person descriptions of the experience (Hammersley, 2004). Phenomenography, rather than looking at what is common, looks at what is different. The result of phenomenographic research is called an outcome space. The outcome space is the collection of the distinct ways in which the phenomenon was experienced. Each of these different ways is referred to as a conception (Marton & Pong, 2005).

Phenomenography and phenomenology were both attractive to this study. Identifying and describing the different ways that PBL students experience SDL would come from the results of the phenomenographic approach; whereas, the phenomenology could result in a composite model ensuing from the experiences of all. Both would add value to the answer to the research question "How do PBL students experience self-directed learning?"

6.3.3. METHODOLOGICAL CHOICE

The approaches to these two methodologies are different. After deeper study of both methodologies, a value decision was made to adopt the phenomenographical approach. For the many reasons described in the following description of phenomenography, the method aligned very closely with the research situation and the PBL model. Ultimately, upon completion of the phenomenography in Chapter 8, the phenomenographic outcome space was developed. It is presented in Chapter 9.

6.4. PHENOMENOGRAPHY

"The main question in a study of learning is the relation between the enacted and the lived object of learning, the learning that is made possible on the one hand and what is actually learned on the other; we also have to study the latter." Ference Marton (Marton & Runesson, 2015)

Phenomenography is both a methodology and a method (Bruce, 1999). It is an empirical, qualitative approach to identify the variety of ways that people experience a phenomenon (Marton, 1981). This section describes phenomenography and the potential it has to be used in a study of self-directed learning experiences of PBL students.

6.4.1. HISTORY AND PHILOSOPHY

Developed in the 1970s by Ference Marton and a group of his Swedish colleagues (Bruce, 1999; Harris, 2011; Limberg, 2008), phenomenography has continually evolved over the past 40 years as a research practice that is most often associated with student learning (Limberg, 2008).

Epistemologically, phenomenography is aligned with interpretivism and constructionism (Bruce, 1999). Phenomenography is referred to as a second-order perspective (Marton, 1981) where the desire is to study the variety of ways people 'experience' a phenomenon. In contrast, a first order perspective would be searching for the meaning of the phenomenon itself. A first-order perspective often contrasted with phenomenography is phenomenology (Case & Light, 2011; Sjöström & Dahlgren, 2002). Thus for this study, phenomenography identifies the variety of ways that PBL students experience self-directed learning (SDL). Further, phenomenography is non-dualistic, meaning that, in this case, self-directed learning and the students' experiences with SDL are not considered as two separate entities. Rather, they are intertwined as one interdependent unit(Linder & Marshall, 2003).

Marton associates phenomenography as the research method for the variation theory of learning:

> *"We cannot grasp just one meaning; it takes two. We can only find new meaning through the difference between meanings… We cannot understand what dry wine is by drinking dry wine only, we cannot understand what linear equations are by seeing linear equations only… But we can learn dry wine through contrast with sweet wine and we can understand linear equations by comparing them with quadratic equations." Ference Marton (Marton & Runesson, 2015)*

Phenomenography is used to identify the variations in a phenomenon using categories of description that illustrate the finite number of ways of seeing the same object of learning *(Marton & Runesson, 2015)*.

6.4.2. DATA COLLECTION

> *"Phenomenographic studies need to have a coherent method throughout, from initial planning stages through collection of data to the analysis. Most importantly, the researcher should have a clear purpose and all efforts should be planned around that purpose." (Mann, 2007)*

In a phenomenographic study, the researcher chooses a sample to represent the widest variety of experiences, typically 15-30 participants (Limberg, 2008). The researcher asks one, or a few, open-ended questions, and then follows up with additional questions in an attempt to get the participant to describe her experiences deeply (Akerlind, 2005). After all interviews are complete and completely transcribed, the researcher seeks to find the set of different ways the entire group experienced the phenomenon (Marton, 1988). Each different way is called a 'conception' (Marton & Pong, 2005) or a 'way of experiencing' (Sjöström & Dahlgren, 2002). The collection of conceptions is referred to as the 'outcome space' (Marton & Booth, 1997). The primary goal of a phenomenography is to identify the outcome space. Further analysis of the outcome space brings to light the defining features of each conception and the inter-relatedness of the conceptions (Booth, Woollacott, & Cameron, 2013). As the outcome space is defined and the conceptions described, the characterizations of each individual's experiences fall away and are replaced by the collectives for the entire group (Booth et al., 2013). This collective becomes the value available as knowledge beyond the group, and the potential value to the greater communities. In the case of a phenomenography of the PBL students on how they experience self-directed learning, the understandings of the outcome space would be of potential value to teaching staff in other PBL programs, academic departments considering PBL implementation, and the greater academic communities that have a stake in the development of self-directed learning as an outcome for engineering graduates.

A phenomenographic study begins with the selection of a topic. Then, a representative sample is chosen. Most commonly, phenomenography research methods start with an open-ended interview (Limberg, 2008). The research and the subject begin with a topic that both share, in terms that are meaningful to both (Ashworth & Lucas, 2000). The opening question begins a conversation, which takes many tangents aiming towards a totality of the individual's experiences. Follow-up questions are meant to elicit meanings and understandings pertinent to the individual's experience and shouldn't come from pre-conceived notions of the researcher (Mann, 2007).

The original question can either pose a specific problem or ask students to describe a situation they have experienced involving the phenomenon. Once the interview is underway, the researcher asks follow-up questions to continue the dialogue. Green (2005) describes three kinds of follow-up questions: 1.) seeking clarification – "Tell me more about…", 2.) playing naïve – "What do you mean by _______?", 3.) exploring contradictions – "You talked about x, now you mention y. They seem to contradict. Can you further explain?". The researcher should use empathy to elicit the lived experiences of the student, being sensitive to his individuality (Mann, 2007), and should never make judgmental comments.

6.4.3. DATA ANALYSIS

Dahlgren and Fallsberg (1991) identify the steps in a phenomenographic analysis:

1. familiarization – read through all transcripts
2. compilation – identify most significant elements in each transcript
3. condensation – reduction to find central parts of longer answers
4. grouping – classification of similar answers
5. comparison – establishment of borders between categories
6. naming – giving titles to the categories

7. contrastive comparison – identifying similarities and differences between categories
8. create a hierarchy of conceptions based on significance of categories

Analysis involves looking for meaning and variation across all of the interviews (Mann, 2007). "The interviews are studied as pools of meanings that relate the students to the phenomenon, containing close to a totality of ways in which it is experienced (Booth et al., 2013)." As the grouping takes place and the researcher begins establishing meaning, he can seek further clarity through activities such as comparisons to theories and discussions with colleagues, doing so through much iteration until the categories emerge with good structure (Booth et al., 2013).

Marton and Booth (1997) provide three criteria for quality in categories (L Mann, 2007):

1. "The individual categories should each stand in clear relation to the aspect of the world under investigation so that each category tells us something distinct about a particular way of experiencing the aspect of the world;
2. The categories have to stand in a logical relationship with one another, a relationship that is frequently hierarchical;
3. The system should be parsimonious, which is to say that as few categories should be explicated as is feasible and reasonable, for capturing the critical variation in the data."

6.4.4. VALIDITY AND GENERALIZABILITY

Validity is first established between the conceptions identified in the outcome space and the interview transcripts. The researcher can use direct quotes from the interviews to establish this validity (Booth et al., 2013). Mann (2007) subdivides validity into two categories, communicative validity and pragmatic validity. In communicative validity, the researcher makes visible the quality of the dialogue during the interviews, demonstrates the coherence of the categories of description, and seeks feedback from other researchers and professionals practicing in the field of study. Pragmatic validity addresses the usefulness in practice. In other words, how well will the results be received and used by the target audience of the study. Since phenomenography is interpretivist in nature, and the results are about the experiences of the people in the study, as well as the experiences of the researcher, empirical, positivist validity is neither possible nor appropriate. Rather, the researcher needs to argue for the validity by demonstrating how they have maintained quality through the entire research process (Marton & Booth, 1997). A phenomenography would provide insights into PBL students' experiences, provide access to the variations in those experiences, result in integrated descriptions of those conceptions, and be generalizable (Bruce, 1999).

6.4.5. ROLE OF THE RESEARCHER

"One of the defining features of the learning study is that it is owned by the teachers: they have to decide what to do and how. Other features are that there is an object of learning identified and that the focus of the study is the relationship between learning and teaching – between the lived and the enacted object of learning." Ference Marton (Marton & Runesson, 2015)

Mann (2007) states "phenomenography takes the position that experience is relational, not purely objective, independent of people, nor purely subjective, independent of the world." Thus, the relationships are central in the creation of knowledge. This puts the role of the researcher as one of being related to both the subject and the phenomenon under study. Mann (Bowden & Green, 2005; Mann, 2007) shows this relationship in the graphic in Figure 6.2.

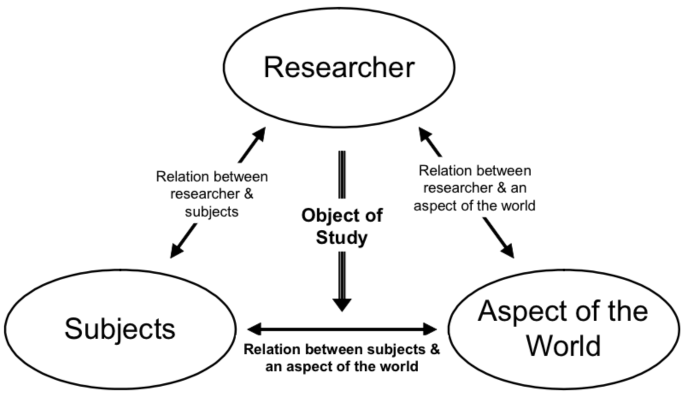

Figure 6.2. Relationships in phenomenography

In the background of any discussion regarding the research of Iron Range Engineering done by this researcher, is the relationship I have as a researcher to the roles I fill at IRE. These roles have been stated before in earlier chapters of the thesis. Briefly, I was the main developer of the idea and the program, serve as the director of the program, am the person responsible for its daily operation and its relationships to the outside world, am the culture keeper within the program, teach technical competences, teach learning about learning seminars, and facilitate project teams. The relationship to the students is intimate and trusting. Thus, on one hand, I should be able to develop deep dialogue and elicit richly described experiences. On the other hand, the challenge of keeping my own past experiences with the students and their experiences of self-directed learning will be great and must be addressed up front and throughout the data collection, analysis, and discussion of results. This relationship is what it is. It exists for any research I could do on the Iron Range Engineering program. The greater question is whether these experiences of students learning, while intertwined with my teaching, and doing research on the learning can be of any pragmatic value to others in engineering education, in general, and specifically in PBL environments. The research needs to be completed and the situation described in such a way that the answer to the above question has the greatest likelihood of being yes.

6.4.6. PHENOMENOGRAPHY IN ENGINEERING EDUCATION

Phenomenography has begun to emerge in engineering education as a qualitative research approach. Daly, Adams, and Bodner (2012) published a phenomenography in the Journal of Engineering Education on an investigation of design professionals' experiences. Zoltowski, Oakes, and Cardella (2012), also in JEE, published on students' ways of experiencing human-centered design. Booth et al. (2013), Adams et al. (2010), Adams et al. (2011), and Mann et al. (2007) have all recently performed phenomenographic studies in engineering education. Further, Case and Light's 2011 JEE article (Case and Light, 2011) proposes phenomenography as an emerging qualitative method in the engineering education community.

6.4.7. PHENOMENOGRAPHY IN MIXED-METHODS

Woollacott, Booth, and Cameron (2013), in their study on student learning practices in large engineering classes, use a combination of quantitative results with their phenomenography to reach their conclusions. Micari et al. (2007) address the interplay between phenomenography, which by itself is a purely qualitative method and quantitative methods. They cite several studies where phenomenographic results are correlated to quantitative data. "Either or both of the qualitative and quantitative phases can be employed in an individual study so that a study can be purely phenomenographic, purely quantitative but based on phenomenographic work or both." (Micari et al., 2007).

6.4.8. OBJECTIVITY

The outcome space is the collection of ways that the students' themselves experienced self-directed learning. The intimate and intertwined nature between the students and the researcher make it inevitable that the researcher's voice will have influence on the results (Sin, 2010). Lincoln and Guba are recognized as having developed trusted frameworks for ensuring credibility in qualitative research (Shenton, 2004). Lincoln and Guba (2001) recommend addressing this issue through reflective commentary by the researcher throughout the research process. The objectivity of the researcher, in this way, is not looked upon as to whether or not he or she has influence on the research process, but rather explicit recognition of how his or her preconceptions and interactions influenced the process and what actions were taken to minimize the influence (Sin, 2010).

6.5. CONCLUSION

This chapter has served to make visible the perspectives of this research and to set forth the methodology of the qualitative aspects of this mixed-methods study. The perspective of the research is interpretivist/constructionist/situational. Further, the methodological decision making process has been made visible. A phenomenographic methodology was selected and described. The mixed-methods approach is to perform a quantitative study to confirm the hypothesis from the literature. Then, perform a phenomenographic qualitative study to seek to understand the SDL experiences of PBL students. In the next chapter, the quantitative method, study, and results are presented and discussed.

CHAPTER 7. QUANTITATIVE METHOD

In Chapter 5, theory and results from the literature predicted that PBL students will develop as self-directed learners and that traditional engineering students do not. As justified in Chapter 6, a mixed methods sequential explanatory design (quan -> QUAL) approach has been selected. In this chapter, the quantitative study is described and results are provided. The results confirm the expectations from the literature, PBL students demonstrate SDL development and traditional engineering students do not.

Creswell (2014) identifies participants, instruments, procedures, and measures as the necessary components of a quantitative method. This quantitative study took place from 2011 to 2015 as part of an NSF funded study that this researcher led as the Principal Investigator. Data analysis took place in mid-2015. The methods used in the study are described in following sections.

7.1.1. PARTICIPANTS

Participant selection was non-random. The number of students available in the PBL program and the comparison groups was low, n=10-25 per group. With this constraint, all students in every group were invited to take the instruments. Approximately 70% of those invited completed the surveys. Further, the surveys were taken over time from 2011 to 2015. Most groups (some groups were only available for either pre- or post) took the surveys *pre-* and *post-* upper-division, where upper-division is defined as the last two years of the engineering bachelor's degree. Pre-PBL students took the surveys just before or early in their first semester of upper division. Pre-comparison group students from regional engineering programs did the same. Post- for both groups took place late in the last semester before graduation or in the few months immediately after graduation. Creswell (2014) identifies experiments where participant selection is non-random as "quasi-experiments." Thus, this quantitative research could be termed a quasi-experiment. Table 7.1 details participants who took the survey instruments by academic year and by PBL vs. comparison groups.

Table 7.1. Participant group sizes by academic year.

Academic Year	PBL	Comparison
2011-2012	n_{pre} = 15 n_{post} =0	n_{pre} = 11 n_{post} =0
2012-2013	n_{pre} = 12 n_{post} = 17	n_{pre} = 14 n_{post} =12
2013-2014	n_{pre} =20 n_{post} =9	n_{pre} = 15 n_{post} =7
2014-2015	n_{pre} =27 n_{post} =16	n_{pre} =32 n_{post} =42

The independent variable is the upper division education, PBL or non-PBL. The dependent variables are the results of the survey instrument.

7.1.2. INSTRUMENT

The approach used to collect data on the SDL abilities of IRE students was the SDLRS, an established questionnaire. The purpose of the quantitative research in the current study is to establish a difference in self-directed learning for PBL and non-PBL students, confirming the results from the literature described in Chapter 5.

As described in Section 5.5, the tool was the Self-Directed Learning Readiness Scale (SDLRS). The SDLRS was originally written by Lucy Guglielmino in the 1970s. It has since been taken by tens of thousands of adults. The validation of the instrument is sound. It predicts a person's readiness for self-directed learning. The instrument is copyrighted. Permission has been obtained to use in this study and to show the instrument to PhD supervisors. Higher scores on this tool indicate higher abilities to solve problems, higher creativity, and higher flexibility in regards to growth (Guglielmino, 1978).

7.1.3. POPULATION

The quantitative study, as mentioned above, involves two groups, pre-test/post-test, and non-random assignment of participants. Creswell (2013) identifies this type of experiment as a "non-equivalent, pretest-posttest, quasi-experimental, control group" design. Visually, the experiment looks like this:

Group A (PBL)	O-----**X**-----O
Group B (Trad.)	O------------O

Figure 7.1. Visual representation of experiment design (O=test, X=PBL education)

The Os represent observation and the Xs represent the education. In this case, the education is a PBL engineering education for the final two years of the engineering bachelor's degree and no X represents traditional engineering education for the final two years. There was not always alignment between groups. In other words, groups sometimes started midyear. Further, there were not always opportunities to observe some groups either pre- or post-. It should also be recognized that the PBL program was dynamically evolving over time.

7.1.4. EXPERIMENTAL PROCEDURE

The steps to the experimental procedure were as follows:

1. Obtain IRB approval.
2. Identify potential student groups (either PBL or non-PBL).
3. Invite all members of the group to take part in the study.
4. Administer the survey via SDLRS website.
5. Collect electronic data.
6. Analyze data using tests of statistical significance.
7. Interpret results.

7.1.5. DATA ANALYSIS

For the SDLRS, a single score was calculated and reported by the company that administered the survey.

Mean-to-mean comparisons were made for the PBL group from pre- to post- and for the PBL vs. non-PBL groups. ANOVA t-tests were administered, using SPSS, to acquire indications of statistical significance. Results are reported in section 7.2, below.

7.2. RESULTS

As noted above, we began an NSF-sponsored longitudinal study of Iron Range Engineering students in the spring of 2011. Instruments from a variety of research domains were administered to students entering the PBL upper-division program (final two years of bachelor's degree) and then again upon their completion. For this PhD study, only the SDLRS instrument results were used. (Other studies used the other instruments.) The results in this study allow for several comparisons:

1. All PBL students who took the instrument before the two-year PBL experience compared to all PBL graduates who took instrument after the PBL experience.
2. The specific cohorts of PBL students who took the instrument both before and after the PBL experience.
3. Non-PBL comparison group, who took the instrument before last two years of engineering bachelor's, compared to a non-PBL comparison group that took the instrument after engineering bachelors.
4. All PBL graduates who took the instrument after engineering bachelor's, compared to all non-PBL graduates who took instrument after engineering bachelor's.

Since 2011, students entering the PBL experience at Iron Range Engineering have been taking the SDLRS instrument. In the spring of 2013, those same students who started in fall 2011 took the instrument at graduation. In total, seven cohorts have taken the instrument before starting their PBL experience, and five cohorts have taken the instrument at graduation. Also beginning in 2011, students from regional colleges and universities were recruited to take the instrument prior to beginning the final two years of their engineering bachelor's. Other groups of students were recruited to take the instrument upon graduation from non-PBL engineering bachelors programs. Due to lack of presence by the researchers at the other regional colleges, contact was not available to get pre- to post- comparison with the same sets of students. This was possible for those undergoing PBL education. Participation rates averaged 70% for students contacted prior to engineering bachelor's and 40% after; whereas, the PBL student groups were at 80% entering and 55% after.

The SDLRS is taken on the lpasdlrs.com website. Results from the survey were downloaded into Excel spread sheets for data organization. For each data set, averages and standard deviations were calculated. Using a t-test and two-tailed p-value ($p<0.05$), statistical significance was sought. Independent sample t-tests were conducted to compare means, using SPSS. The SDLRS results come in two formats, a raw score on a scale from 0-290 and a percentile compared to all adults who have taken the instrument. A score of approximately 214 corresponds to the 50^{th} percentile. For this analysis, percentiles were used in an effort to have more meaning.

7.3. COMPARISON 1: ALL PRE-PBL VS. ALL POST-PBL

From 2011 to 2015, 74 PBL students (all pre-PBL) took the SLDRS prior to the PBL program. Forty-two graduates (all post-PBL) took the instrument at graduation. Significant differences were observed between performance prior to the PBL experience (M = 66.1, SD = 23.5) and upon graduation from the PBL program (M = 75.8, SD = 17.5), t = 2.539, p<.05.

Table 7.2. SDLRS results for PBL.

	All Pre-PBL	**All Post-PBL**
n	74	42
Average (M)	66.1	75.8
Standard Deviation (SD)	23.5	17.5
pre-post T-score	2.359	
pre-post two-tailed P-value	.013	

7.4. COMPARISON 2: PRE-PBL VS. POST-PBL SAME COHORTS

Comparison 2 looks specifically at cohorts who took the instrument both before and after the PBL program. Forty-seven PBL students (pre-PBL same cohorts) from these cohorts took the SLDRS prior to the PBL program. Thirty-two graduates (post-PBL same cohorts) from the same cohorts took the instrument at graduation. Significant differences were observed between performance prior to the PBL experience (M = 60.1, SD = 24.8) and upon graduation from the PBL program (M = 76.6, SD = 16.1), t =3.591, p<.05.

Table 7.3. SDLRS results for PBL – same cohort.

	Pre-PBL same cohorts	**Post-PBL same cohorts**
n	47	32
Average	60.1	76.6
Standard Deviation	24.8	16.1
pre-post T-score	3.591	
pre-post two-tailed P-value	.001	

7.5. COMPARISON 3: NON-PBL BEFORE FINAL TWO YEARS VS. NON-PBL GRADUATES

A group of 72 students (pre-non-PBL) were recruited to take the SDLRS prior to the final two years of engineering bachelor's degree at a regional university in traditional engineering programs. A different group of 61 graduates (post-non-PBL) from the same universities took the SDLRS upon graduation. Significant differences were not observed between performance prior to entering the traditional final two years (M = 56.0, SD = 26.5) and upon graduation from the traditional program (M = 61.5, SD = 26.8), t =1.168, not significant p>.05.

Table 7.4. SDLRS results for non-PBL.

	Pre – Non-PBL	**Post – Non-PBL**
n	72	61
Average	56.0	61.5
Standard Deviation	26.5	26.8
pre-post T-score	1.168	
pre-post two-tailed P-value	.245	

7.6. COMPARISON 4: PBL GRADUATES VS. NON-PBL GRADUATES

The final comparison contrasts the PBL graduates with graduates from the traditional engineering programs (Non-PBL). Forty-two PBL graduates took the SLDRS and 61 non-PBL graduates took it. Significant differences were observed between performance of the PBL graduates (M = 75.8, SD = 17.5) and the non-PBL graduates (M = 61.6, SD = 26.8), t =3.290, p<.05.

Table 7.5. SDLRS results for PBL vs. non-PBL.

	PBL Graduates	**Non-PBL Graduates**
n	42	61
Average	75.8	61.5
Standard Deviation	17.5	26.8
pre-post T-score	3.290	
pre-post two-tailed P-value	.001	

7.7. DISCUSSION

As discussed in Chapter 5, the literature indicated that non-PBL students, in traditional engineering programs, showed little if any gains in SDLRS score. The results of this study agree with the previous studies. There were no significant gains for students from entering to leaving the non-PBL traditional engineering program ($t=1.168$, two-tail $p=0.245$, not significant at $p<0.05$).

The literature also indicated that PBL experiences could result in statistically significant gains in SDLRS score. Again, the results of this study agree with the previous studies. There were significant gains for students in the PBL upper division (last four semesters of bachelor's degree) engineering program ($t=3.591$, two-tail p-value=0.001, significant at $p<0.05$).

Figure 7.2 is a box and whisker plot showing how the mean SDLRS percentiles, standard deviations, and minimums/maximums compared for the comparisons listed in Sections 7.1 through 7.4. In comparisons 1, 2, and 3, which are contrasts of SDLRS scores from prior- to post- PBL or non-PBL education (during the final two years of engineering bachelor's degree), the SDLRS mean scores increased. However, as described above, the differences shown in comparisons 1 and 2 are significant, whereas comparison 3 is not. Comparison 4 is a contrast of post-graduation for PBL vs. non-PBL traditional education. Again, the difference is significant.

It is interesting to note that the standard deviations and max/min differences substantially decreased across the two years of education for PBL students, whereas these decreases are not noted for non-PBL comparisons.

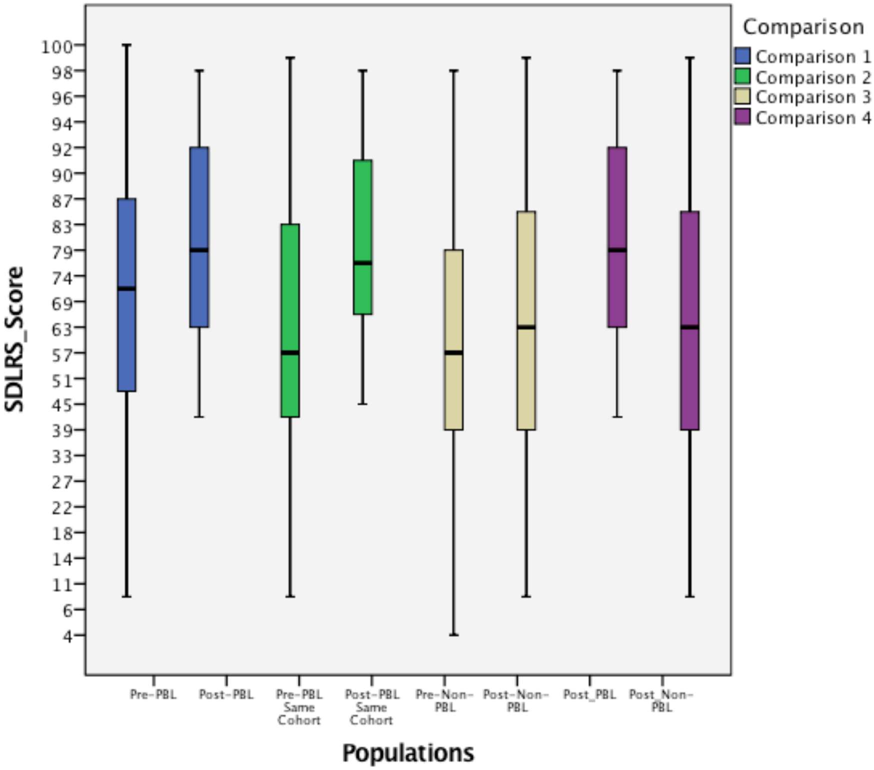

Figure 7.2. Box and whisker plot by comparison

The commercial aspect of the SDLRS, and the fact that its averages are the result of over 120,000 adult responses enables some comparisons between the results of this study and the previous studies that used the same instrument. Below, in Table 7.6, the post-scores of the PBL students in this study are compared with the post- scores in the studies from the literature. The post-score for all PBL graduates of 75.8 percentile compares with the other study post-scores of 53 and 66.

Table 7.6. Comparison of post-scores from this PBL study and studies in the literature.

Study	Post- Score (percentile)
Litzinger (n=1000)	66.0
Jiusto (n=259)	53.0
This study non-PBL (n=61)	61.5
This study PBL (n=42)	75.8

7.8. VALIDITY

In this study, there are many time, group, and observation confounding factors. There are threats to validity in any study. Creswell (2013) subdivides threats into internal and external categories. The threats that arise in this study are an internal threat of history and an external threat of interaction. The threat of history is that due to the passing of time during the experiment, events may occur that could potentially influence the outcome. In this study, which took place over four years, there were events that could influence the outcome. For example, the PBL program evolved and some of the groups were not available for either the pre- or post-survey. Interaction and setting refers to the setting of a group study that may have characteristics different enough from other groups that the results are not generalizable. The small (<50 students) environment of Iron Range Engineering could lead to this issue.

These threats to validity would make a purely quantitative study difficult to validate and prove credible. The purpose of this quantitative study, however, is to provide macro level information about the greater group that underwent PBL, so as to establish need for the findings from the qualitative study. The existence of data from the greater group of non-PBL students can serve to provide a contrasting background for interpreting the development of the PBL groups.

7.9. CONCLUSION

The research question "How do PBL students experience self-directed learning?" might infer that PBL students develop differently than non-PBL students. The purpose of this quantitative study was to analyze this assumption. Theory and the literature tended to predict that PBL students experienced more development as self-directed learners than non-PBL students. Using this one tool, the SDLRS, the results shown above confirm that the PBL students at Iron Range Engineering did develop as self-directed learners, whereas, a comparison group of non-PBL students did not. This was analyzed from four perspectives, as detailed in the four comparisons in Sections 7.3 to 7.6. In the following chapters, a qualitative study is detailed, with the purpose of explaining this growth of PBL students as self-directed learners.

<u>FINDING # 1</u> – Quantitative Result. Confirmation of expectation from theory and literature that PBL engineering students develop as self-directed learners during engineering education, whereas, traditional engineering students do not.

CHAPTER 8. QUALITATIVE STUDY: METHODS AND RESULTS

"…in the workplace, a lot of times somebody will come up to you and say I need this to be done and they could full well know that you've never touched it before, you have no idea where to even begin in something like that. However, they know that because of what's on your resume that you can figure it out. If you have certain questions you know whom to go to or what to go to, to try to figure this out on your own. So for me, the self-directed learning has never stopped and will never stop now. There's always going to be another challenge out there and especially in the industry that I'm in. It's always changing forever." [person U]

For the qualitative study, Dahlgren and Fallsberg's (1991) steps of phenomenographic analysis were followed. The transcripts were read multiple times, each time resulting in an increasingly sophisticated perspective of the participants' experiences and views. Two explicit perspectives result from this analysis. First, the phenomenography (Chapter 9) provides a perspective of the different ways the participants experience SDL. Six different "ways of experiencing" are identified. Secondly, a "composite model" (Chapter 10) emerged, wherein all of the processes used by the participants are combined to communicate a model for self-directed learning. Direct quotes from the interviews are used throughout to describe, firsthand, the views and feelings of the learners. In the following sections, the qualitative method is explained.

8.1. QUALITATIVE METHOD

Sin (2010) puts forth considerations to ensure rigor and quality in each phase of a phenomenographic study. "…the consideration of quality in phenomenographic research begins at the outset of the study, from stating the research question(s) and justifying the appropriateness of the phenomenographic method and at each stage of the research process."(Sin, 2010).

8.1.1. RESEARCH QUESTION AND THE PHENOMENOGRAPHIC METHOD

The research question: "How do PBL students experience self-directed learning?" is addressed in the qualitative study by investigating students' conceptions of the phenomenon of self-directed learning. Svensson (1997) defines phenomenography as the study of "peoples' lived experiences and conceptions." This study analyzes how the PBL students experience and conceive their self-directed learning ability.

Section 6.4, provides detail in the selection of phenomenography, implicitly justifying the appropriateness to this study. Explicitly, phenomenography aligns with the study by specifically describing the collective variations of how PBL students conceive self-directed learning. This collective variation, described as the outcome space, was identified through structured, one-on-one interviews between the participants and the researcher, in a non-dualistic engagement, to explore their experiences. This method's appropriateness will be confirmed through its ability to provide value, beyond the study, to others wishing to consider how PBL can benefit the development of SDL abilities of engineering students in other environments (Sin, 2010).

8.1.2. ANALYZING DATA

"Analysis is guided by the research questions of the study. During analysis the researcher seeks an empathetic understanding of what is involved in the phenomenon of study derived from interviewees' descriptions of what it means to them. The researcher tries to maintain a participant perspective assuming the interviewees experiences and ways of reasoning are logical, even if they do not appear as such at first. Phenomenographic analysis is an hermeneutical process."
Limberg (2008)

In Chapter 6, Dahlgren and Fallsberg's (1991) eight-step model for data analysis was chosen for this research project. Briefly, the steps are 1) familiarization, 2) compilation, 3) condensation, 4) grouping, 5) comparison, 6) naming, 7) contrastive comparison, and 8) creating a hierarchy. Based on this work, an outcome space will be developed. The outcome space will include both the referential aspects, which are the global meanings of each conception, as well as the structural aspects, which are the features of each referential aspect (Limberg, 2008).

8.1.3. SELECTING PARTICIPANTS FOR THE STUDY

Marton and Booth (1997) advocate for selecting a wide variety of participants so that the widest possible variations of experiencing can be identified. The number of participants in a typical phenomenographic study is 15-20 (Trigwell, 2000). The group to be studied included the PBL students graduating from Iron Range Engineering in the 2014-2015 academic year, as well as recent graduates. Twenty-seven people participated in the study. Selecting this population allowed for a wide possible variety of conceptions, while still being in a range that is reasonable for the time intensive transcription and data analysis. Table 8.1 displays the demographic data of the participants. Each of the divisions parallels the overall population of Iron Range Engineering.

Table 8.1. Demographic information on participants

Demographic Category	**Number**
Male	**23**
Female	**4**
Under 25	*17*
25 and Over	*10*
Mechanical	**13**
Electrical	**8**
Other Engr. Major	**6**
Graduate in practice	*15*
Student near graduation	*12*

8.1.4. COLLECTING DATA

Data was collected by audio recording the interviews and transcribing them verbatim. The first questions were used to help the interviewee become comfortable and for the interviewer and the interviewee to arrive at a common language. Following the introduction, structured questions, aimed at the phenomenon of self-directed learning, were asked. A pilot interview was employed, as a test case, for learning how the interview process worked, vetting the interview questions, and learning from initial responses to further develop questions used in later interviews (an accepted phenomenographic technique per Limberg (2000)).

The initial dialogue aimed to look both backward and forward:

> "Think of a technical topic where you took on the greatest level of ownership in the learning, describe the self-directed learning processes you used to complete the study."

and

> "In a few months, you will be in the engineering workforce. Describe how you will use self-directed learning processes to acquire the next technical competence you will be required to attain."

Following the protocol of phenomenographic interviews, follow-up questions were then asked to empathetically seek out, as deeply as possible, the perspectives and experiences from the students, without imparting the views or perspectives of the questioner (Limberg, 2000). It is, however, necessary to recognize that the topic is jointly explored between the researcher and the interviewee (Marton, 1994). It is just that the researcher must "bracket" his or her views to prevent imparting beliefs onto the interviewee (Mann, 2007).

Mann (2007) and Sin (2010) identify critical aspects regarding follow-up questions as gleaned from a variety of other publications:

- Judgmental comments should never be made by the interviewer
- Seek clarification
- Play naïve
- Explore contradictions
- Use empathy to further engage life experiences of interviewee
- Do not import earlier research findings to the conversation
- Do not assume pre-determined conceptions or meanings
- Do not impose researcher's personal knowledge and beliefs
- Do not introduce new terms into the interview
- Do not correct the interviewee
- Give the interviewee time and space to reflect and talk
- Avoid showing facial expressions of agreement or disagreement, but remain attentive
- Do not ask leading questions

These guidelines were followed.

8.1.5. TRANSCRIBING INTERVIEWS

Verbatim transcription, which doesn't permit the transcriber to interpret or restate, is the accepted method in phenomenography and is important for helping ensure reliability and validity of the data (Limberg, 2008). The interviews were transcribed verbatim by a person external to the research.

8.1.6. VALIDITY OF QUALITATIVE STUDY

As identified in Chapter 6 (Sections 6.4 and 6.5), verification of a phenomenographical study is addressed through the generalizability of the work and the role of the researcher. Validity can further be addressed through the use of quotes from the participants in the analysis, as opposed to only the interpretations of the researcher. In this study, quotes were extensively used to put the words of the participants' front and center for the reader to interpret their thoughts.

The intent of the study is to provide knowledge for others to consider as they contemplate the implementation of PBL or the development of self-directed learning skills in students. The findings of the study have been purposefully generalized for use by others. The assessment of this generalizability will be determined by the extent to which others ultimately use the work.

The role of the researcher has been openly discussed throughout the design and implementation of the research study. I am intimately intertwined in the lives of the participants and the implementation of the PBL program under study. This intimate role is recognized for the value it might add and for any adverse effects it might have. Several steps were taken to minimize adverse influence of these relationships on the outcome of the work. The steps include the following: performing a pilot interview that was observed by colleagues, having other researchers perform some of the interviews, attempting to blind the identity of participant's transcripts to the researcher during analysis to minimize the influence of previous shared experiences on the interpretation of results, and being explicit with the interviewees in regards to desire for openness.

8.2. FIRST READING

Familiarization is the first read-through of all transcripts. During this phase, similarities that emerged are identified through the common descriptions used as participants described what self-directed learning and metacognition meant to them. It is noted that these are the words of the participants. Emerging similarities included:

- identifying resources
- objectives/goals
- evaluation or assessment
- learning activity
- monitoring and feedback
- self-reflecting
- automation
- regulation for future
- prior knowledge
- responsibility
- schedule
- validation

Differences emerged in comparing the variety of ways that the engineers embraced their approach to SDL. Some embraced SDL as being a very deliberate and complete process, while others treated it as being automated, requiring little explicit attention. Another contrast came between participants who viewed self-directed learning as being wholly independent, with no guidance from others; whereas, on the other end of the spectrum, some considered themselves as managers of their learning, embracing a wide variety of instruction from teacher-led to person-led. One more difference arose between people who viewed SDL as a tool they would use when the need to learn arises while others were motivated to use SDL in a continuous state of improvement.

Upon identifying the similarities that emerged from the first reading, NVivo queries were run to identify word frequencies, counting the number of times the SDL elements were mentioned during the interviews. The data was looked at from two perspectives: 1) In how many interviews did each of the SDL aspects arise? and 2) How many aspects did each participant mention in total? The results are shown in Tables 8.2. and 8.3

Table 8.2. Number of interview participants who mentioned the aspect of self-directed learning (27 participants)

SDL Aspect	Count
identifying resources	22
objectives/goals	19
evaluation or assessment	16
validation	16
regulation for future	15
responsibility	14
schedule	14
learning activity	13
monitoring and feedback	9
self-reflecting	8
prior knowledge	7
automation	4

Table 8.3. Number of aspects of self-directed learning mentioned (11 possible)

Number of Aspects Mentioned	**Count of Participants**
0	0
1	0
2	1
3	5
4	4
5	4
6	3
7	8
8	3
9	0
10	0
11	0

Further keywords were queried in NVivo in an attempt to identify any further aspects that did not emerge from the first reading. Aspects that emerged were cyclic process (11 out of 27), motivation (10 out of 27), retention (7 out of 27), and documentation (4 out of 27). These aspects were considered in further development of results.

From the first reading of the transcripts and the NVivo results, emerged a visual model of self-directed learning. The model, shown in Figure 8.1, accounts for the cyclic and iterative aspects of self-directed learning. The model is an adaptation of a model for the engineering design process used at Iron Range Engineering (see Chapter 4). The purpose of using this model at this point in the analysis was to create a visual representation of the composite process described by students, as captured in the first reading, and the NVivo word-count results. Two elements originally identified in the familiarization phase, responsibility and automation, are not included in this model as they are not actions of a learning model, but rather attributes of implementing the model.

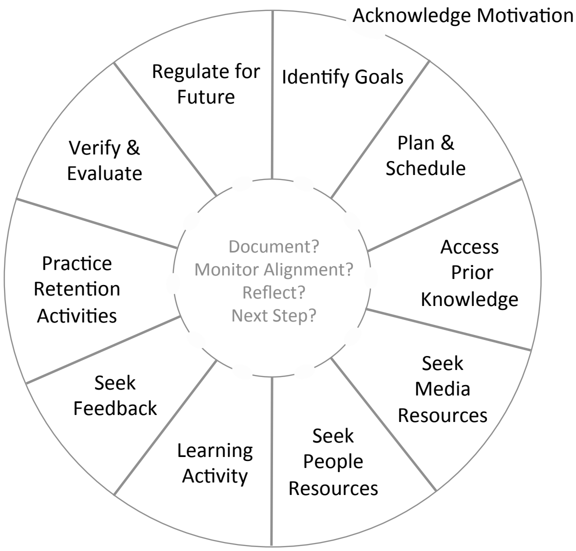

Figure 8.1. SDL graphic.

For each of the steps in this model, participants explicitly acknowledged it, implicitly inferred it, tacitly used it, or did not have the step in their learning. Following is a brief interpretation of the participants' views of each step in this model. Upon the development of the model, a second reading of each transcript took place using the model to follow the pathways that individuals followed and noting which steps were explicitly identified. The second reading resulted in the development of a more comprehensive model and further understanding of the ways these PBL participants experienced self-directed learning, which is described in a future section. This first model can be visualized as a round "house" with each of the sections around the perimeter being a "room." The learner enters the house exhibiting motivation and deciding to undertake self-directed learning. Traveling from one perimeter room to another requires going through the "center" room. In the center room, alignment of the work is checked, documentation is confirmed, reflection is completed, and the next step (or room to enter) is determined.

Interpretation of participants' views of each element:

- Acknowledging motivation is seen as the gateway to beginning a self-directed learning process. Without intrinsic, or some level of extrinsic motivation, there is no reason for SDL to be initiated.

- Stating objectives/goals is a way to characterize what is to be learned and to have a standard against which to measure progress and success.
- Planning and scheduling is compiling the list of steps to be taken and creating the time frame in which they are accomplished.
- Accessing prior knowledge is the recalling of what is already known. It is the identification of the fundamental principles so that the new learning can be built on, and guided by, the understood principles.
- Seeking media resources is finding and using information in print or in an electronic medium such as videos or digital publications.
- Seeking people resources is reaching out to, and questioning, experts such as co-workers, instructors, or vendors.
- The learning activity, often mentioned by interview participants as "doing the learning", is the act of using the prior knowledge, additional resources, and critical thought to create a new conceptual model of understanding.
- Seeking feedback from a person with some level expertise is required to confirm the model or find parts of the model that are inaccurate or incomplete.
- Practicing retention activities is done to make the new learning "stick" and be accessible for transfer in the future. Examples may include practicing retrieval or performing reflection.
- Verifying and evaluating can be seen as confirming the accuracy of the conceptual model through testing and use, finding ways to prove or disprove the understanding, or to quantify the extent or quality of the model.
- Regulating for the future is the metacognitive action of explicitly evaluating the learning process and contemplating improvements in future learning processes.
- Documentation of the conceptual model, during the process or at the conclusion, is the recording of it in some physical or digital manner for later use.
- Alignment monitoring happens as the learner using the model goes from one stage in the model to another, and before doing so, does a check to make sure that there is alignment between the work being done and the objectives, or between the work being done and the schedule, etc.
- Reflection is the revisiting of the experience in a way that puts meaning to it and connects it to future use.
- Next steps is the decision made by the learner, at any point, to move to another aspect of learning or to cease the SDL cycle.

8.3. SECOND READING

Upon conclusion of the development of this model, a second reading took place. During the second reading, the model from Figure 8.1 was used to chart which of the 15 aspects above were described by the participants. This was done to look with more context at the participants' meanings. Each participant's approach was characterized on a continuum as to whether they were automated vs. intentional, linear vs. cyclic, saw SDL as a need vs. a want, considered SDL as independent or involving other people, and whether their overall approach was novice vs. sophisticated. Further, the reading was undertaken to identify if any further aspects of SDL emerged. Two new aspects emerged from the second reading. The aspects were monitoring efficiency and personal attitude. Figure 8.2 shows a sample analysis using the first model in the second reading.

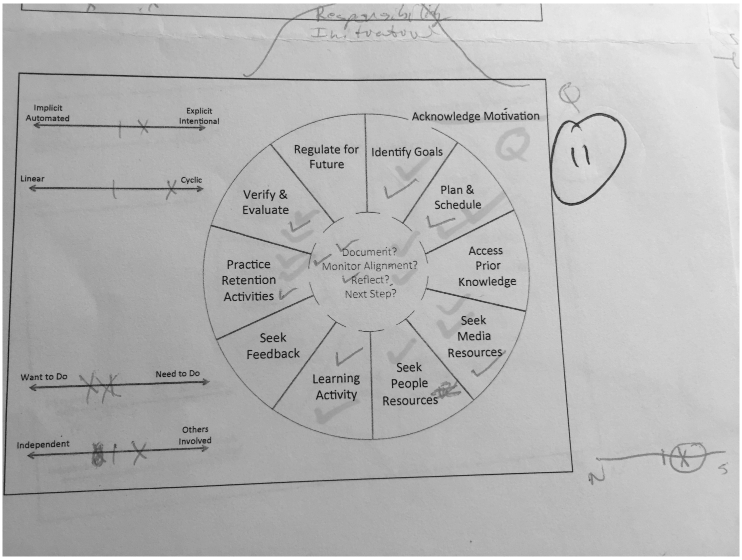

Figure 8.2. Sample analysis from second reading.

The results shown in Tables 8.3 and 8.4 are from two perspectives. First, looking at how many participants mentioned each "aspect" of SDL. Then from the point of view of how many "aspects" did each person mention. There were 15 identified aspects of self-directed learning at this point in the analysis and 27 participants. Several notable conclusions can be drawn from this analysis:

- PBL students, as a whole, identify with the majority of elements of SDL.

- Highly utilized aspects of SDL are *goal setting, performing learning activities, verifying results, and seeking resources*.
- An underutilized element of SDL is *considering the next step in learning*.

Table 8.4. From 2nd reading, number of interview participants who described the use of the aspect of self-directed learning (27 participants).

SDL Aspect	**Count**
Seek media resources	27
Verify/evaluate	26
Perform learning activities	26
Set goals/objectives	25
Seek people resources	23
Reflect	21
Monitor alignment	20
Acknowledge motivation	18
Access prior knowledge	16
Plan/schedule	15
Document	14
Regulate for the future	14
Seek feedback	14
Practice retention activities	13
Consider next step in learning	6

Table 8.5. From 2nd reading, number of aspects of self-directed learning mentioned per participant (15 possible).

Number of Aspects Mentioned	Count of Participants
5	1
6	1
7	1
8	3
9	1
10	7
11	5
12	5
13	1
14	1
15	1

***FINDING #2* – Level of Sophistication of Self-Directed Learning. Emerging from the qualitative study is a view of how PBL graduates identify, view, and use the elements of self-directed learning. PBL students identify 15 SDL elements. On average, they use more than 2/3 of the identified aspects. Highly utilized SDL aspects are "goal setting", "performing learning activities", "verifying results", and "seeking resources." The underutilized element of SDL is "considering the next step in learning."**

The qualitative study described in this chapter resulted in one finding of this PhD study and set the stage for the development and analysis of two additional findings. In the upcoming chapters, the phenomenographical outcome space and a composite model are identified and analyzed.

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CHAPTER 9. PHENOMENOGRAPHIC OUTCOME SPACE

The phenomenographical steps of familiarization, compilation, and condensation all took place in Chapter 8, as described in the sections titled "first reading" and "second reading." Now, in Chapter 9, the phenomenography continues with grouping, comparison, naming, contrastive comparison, and creating a hierarchy. Direct quotes from the students are used, with interpretation, to identify the outcome space and create the boundaries within the space. Theory and the literature from Chapters 2 and 5 are used to verify the results in the analysis portion of the chapter.

9.1. DEVELOPMENT OF PHENOMENOGRAPHIC MODEL - GROUPING

This viewpoint comes from identifying the different ways that the participants experience SDL. Each participant, at some point during the interview, communicated his or her views on self-directed learning. The responses seemed to take on a definitive tone. For example:

> *"…being responsible and taking over without being told what to do" or*
>
> *"…you develop a set of skills to where you learn an efficient process that helps you acquire new knowledge at a faster rate than you normally would."*

As all responses were being aggregated, key words and phrases began to emerge. The key words included: Independence, ownership, responsibility, value, outcome, management, efficiency, initiative, learning, motivation, effectiveness, future use, evaluation, process, control, behavior change, researching, retention, continuous improvement.

A quote was extracted from each transcript in an effort to capture each individual's way of experiencing self-directed learning. After multiple readings, the 19 key phrases above began to combine through interpretation of common meaning into fewer categories. For example, initiative and motivation as seen in these two excerpts:

> *"…you have the skills and ability to recognize when you need to know more than you currently do or you have a desire to and you take the initiative to find ways to learn it…" and*

> *"…that I pick something I'm motivated to learn about, instead of someone just telling me to do something…"*

were combined into one category where the intents of the students seemed similar. Further, the new categories began to develop distinct boundaries from one another. An example boundary would be how some students were focused on who was doing the learning (independence or responsibility), while others were focused on the outcome of the learning (future value or effectiveness), the process of learning (managing the act), and the impetus for the learning (motivation or initiative). Six primary themes emerged.

9.2. PHENOMENOGRAPHIC MODEL - NAMING

9.2.1. PRIMARY THEMES

The primary themes represent how the participant identifies what self-directed learning means to them. The themes are *independence, managing the act of learning, owning the responsibility of learning, focusing on the value or future use of the learning, efficiency/effectiveness of the learning,* and *taking initiative or being motivated*. Figure 9.1 shows the primary themes in a tree-map graph where the relative size of the box demonstrates the frequency of the primary theme.

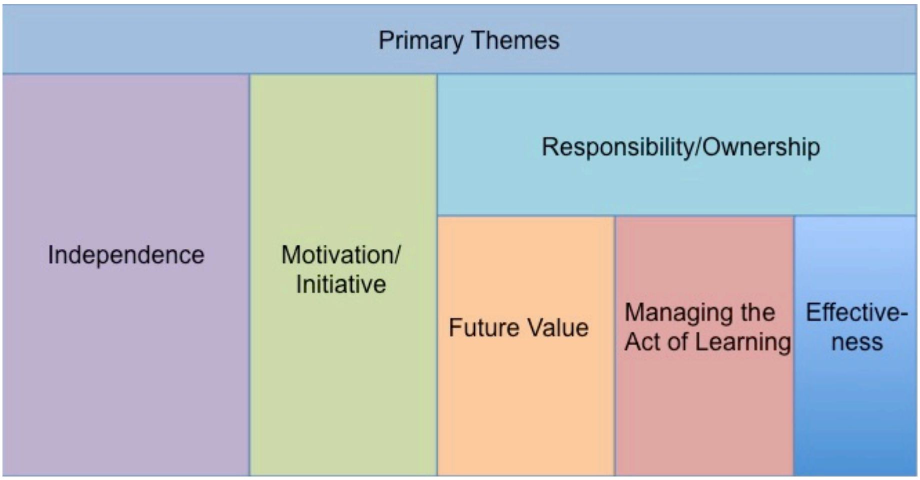

Figure 9.1. Differing perspectives of self-directed learning

Following, under the headings described in Figure 9.1, are the ways in which the PBL graduates describe self-directed learning. These descriptions, in the words of the PBL participant, indicate the differing ways they experience self-directed learning.

9.2.1.1 Independence

Independence, as experienced by the participants, is the view of self-directed learning as being done completely by the individual without any help from or interaction with others. They view themselves as being on an island alone.

> *"…being able to work through things on my own and be independent, not having to bug other people and constantly go running to someone for what's going to happen, what needs to happen, say, in a job or in a project, and being efficient and working, being self-directed, being efficient and knowing the best way to get to things." [person L]*

9.2.1.2 Motivation / initiative

The learners consider the self-directedness of self-directed learning to be the act of beginning. They focus on the desire to learn as being more important than the acts of learning. They view the aspiration to start and continue the learning as being self-directed.

> *"That I pick something I'm motivated to learn about, instead of someone just telling me to do something. So it gives me a passion behind it, which I think in turn makes me remember it and care about it more." [person J]*

9.2.1.3 Responsibility / ownership

In this "way of experiencing", the participants view the learning as being directed by themselves. They take accountability for the actions of learning. They view themselves as the "CEO" of their learning.

> *"I take responsibility for my learning; I don't leave it up to an instructor per se. If they present a topic or use a word or a concept, if it isn't gone into detail in a course or during the lecture, learning conversation, I make a note, or make a mental note and I go research that and dig into, you know, what it is." [person W]*

9.2.1.4 Future value

Here the learners were much less focused on the ownership, leadership, or management of the learning and more focused on the value of the learning.

They view the learning as the final outcome rather than as the process.

> *"…you're learning something to make it stick better or make it mean more instead of just reading to memorize or learning to get through a class, but to actually be able to recall it as useful information and be able to use it in some kind of application or other context later on." [person B]*

9.2.1.5 Managing the act of learning

In this category, the learning rather than happening from some sort of top down model with the learner at the top, is experienced with the learner in the middle managing all of the various actions and interactions. The learners view themselves as the "project managers" of their learning and recognize the involvement of others as being contributors to their learning.

> *"…researching a different subject or different topic that you're interested in and then going in depth and doing your own style of learning… finding your own pattern of how you learn effectively and then continuing to use it and if there's any extra like key things that you learn along the way, you know, you kind of learn how other people learn more effectively and maybe that worked for you, so you pick up some ideas from them." [person M]*

9.2.1.6 Effectiveness

These learners, when experiencing self-directed learning, are concerned with the expediency and effectiveness of the learning. They view self-directed learning as being the level to which the processes are like lean manufacturing.

> *"It means the capability of achieving those resources through a systematic and efficient, time efficient way." [person T]*

9.2.2. SECONDARY THEMES

The six primary themes were sometimes also mentioned as a secondary theme. For example, in the following quote, the participant describes self-directed learning as *managing the act of learning* while also mentioning *effectiveness*:

> *"…researching a different subject or different topic that you're interested in and then going in depth and doing your own style of learning… finding your own pattern of how you learn effectively and then continuing to use it and if there's any extra like key things that you learn along the way, you know, you kind of learn how other people learn more effectively and maybe that worked for you, so you pick up some ideas from them." [person M]*

To quantify, *effectiveness* was secondarily mentioned by six (of the 28) participants, *future value* was mentioned by four, *managing the act of learning* by two, and *motivation/initiative* by one.

Analysis of the phenomenography takes place from three perspectives in the following sections as boundaries are created and the ways of experiencing are discussed in detail.

9.3. CONTRASTIVE COMPARISON

9.3.1. CREATING BOUNDARIES

This phase of the phenomenography is meant to identify similarities and differences to create boundaries between the categories. To do so, the theoretical perspectives highlighted in Chapter 5 are invoked. Lifelong learning, metacognition, self-regulated learning, self-directed learning, and self-determination theory, as well as Stolk's framework for self-directed learning (Stolk et al., 2010) serve as a background to delineate the "ways of experiencing." Differences are highlighted as a particular category or categories stand apart by not being a part of the language used in the descriptions. For example, self-regulated learning highlights *responsibility/ownership*, *managing the learning act*, the *future value* of the knowledge, *motivation/initiative*, and *effectiveness/efficiency*, but does not highlight the *independence* aspect, thus setting independence apart as being different. Likewise, similarities are identified through categories being common. For example, metacognition focuses on the categories of managing the act, future value, and effectiveness/efficiency. Following in Table 9.1, the 6 categories from the "ways of experiencing" are listed as they apply to the five theories. This table highlights the similarities and differences between the ways of experiencing categories.

Table 9.1. Alignment of ways of experiencing with theories

	Lifelong Learning	Meta-cognition	Self-Regulated Learning	Self-Directed Learning	Self-Determine. Theory
Independence	X			X	
Respons. Ownership			X	X	
Managing the Learning Act	X	X	X	X	
Future Value		X	X		
Motivation / Initiative			X	X	X
Effectiveness Efficiency		X	X	X	

<u>Lifelong learning -</u> As is portrayed in the following quote that was used to describe lifelong learning in Chapter 5, it focuses on the categories of *independence* and *future value*. From the Washington Accord, "lifelong learning (is the) preparation for and depth of continuing learning: recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change." (Washington-Accord, 2015). Person X demonstrated these beliefs:

> *"…you have kind of the ambition or drive to be kind of in a continuous state of improvement… I look at it as continuously bettering yourself in your trade or the parts of your life where it kind of benefits you." [person X]*

<u>Metacognition -</u> As described in Section 5.2, is focusing on monitoring the act of learning and using the results of that monitoring (*effectiveness/efficiency*) to regulate the actions taken during the learning (*managing the act of learning*). Metacognition is done in the "service of a concrete goal or objective (*future value*)" (Flavell, 1976).

> *"…what process really worked for learning bearing calculations that I can apply and help me to learn the material faster, better and more thoroughly with the final element analysis?" [person Z]*

> *"…when you execute your plan, make changes as you go, if needed. So you kind of have that feedback process throughout everything. And then once, let's say you learned it, then that's when you kind of go for the final, did I actually learn it, it's kind of another feedback step, but it's more defined. There should be feedback in everything…" [person F]*

Self-regulated learning - While self-regulated learning includes in its title the word self, it is not characterized as independent in the way that the interview participants claimed independence. They leaned more towards isolation.

> *"...go out and learn basically on your own with very little involvement from, from an instructor or an outside source." [person N]*

To the contrary, SRL is not about isolation. Zimmerman (1986) focuses on the self as participatory, rather than independent: "Students are self-regulated to the degree they are metacognitively, motivationally, and behaviorally participants in their own learning." Further descriptions of SRL, as included in Section 5.2, identify all other categories. This separates independence from the others.

Self-directed learning - Similarly, the theories of self-directed learning, as described in Section 5.2, isolate one of these categories through omission. The category is *future value* of the learning. The future value may be implicit in SDL. However, the other categories are explicitly identified. The theory of SDL focuses more on the processes of learning and attributes of the learner than on the outcome of the learning, as can be seen in this excerpt from Section 5.2 "A self-directed learner possesses the personal autonomy and self-management attributes necessary to employ her metacognitive knowledge and metacognitive actions in a self-regulated learning process while learning in either learner-control or autodiaxy environments."

Self-determination theory – As described in Section 5.4, SDT explicitly focused on personal motivation. SDT addresses "the motivations that cause the learner to start any phase of a learning cycle and impact the levels to which the knowledge is accessed and the actions are executed. Self-determination theory provides a framework for interpreting the impact of motivation on self-directed learning." This explicit focus on motivation by self-determination theory sets motivation/initiative apart from the other categories.

> *"I feel like I learn a lot better when it's more carefree than when something's pressure. 'Cause when you have pressure, when it involves learning you stop caring about what, what you're actually learning." [Person E]*

9.3.2. CHARACTERIZATION USING STOLK FRAMEWORK

Figure 5.3 in Section 5.6 is the framework designed by Stolk et al. (2010) to characterize self-directed learning. In their publication, each of the 16 cells of the four by four matrix is identified with appropriate attributes. The four columns represent phases of self-direction (intention, planning/forethought, monitoring/control, and reflection/reaction), whereas the four rows are the areas of self-direction (cognition, motivation, behavior, and context). To further delineate the six categories of self-directed learning identified in this phenomenography, they can be placed in Stolk's framework:

Independence, as described by the interview participants, is not well represented in the Stolk framework. It is implicit in many descriptors such as self-actualizing, self-recording, or self-observation, but not explicit in the way described by the interview participants:

> *"…going out to find information independently and learn the information to be able to use it in the future …so everything that I've done has been I guess by myself and then that requires self-direction in order to learn the material." [person V]*

Responsibility/ownership, as described by the participants, was most aligned with the behavior area of self-direction:

> *"…taking that ownership and then forming your own plan for the direction that you want within your learning." [person Y] And: "I'm the one responsible for setting some sort of schedule to be able to learn it. It means I have a vested interest in what I'm going to be learning, means I have to set some sort of timetable for myself." [person I]*

The descriptors used by Stolk that align with this category are choice to engage, planning, and acquisition of resources.

Managing the act of learning aligns with cognition through need recognition, choice of topic, selection of strategies, and judgments of learning:

> *"…being able to know what you need to know. So kind of defining it and then also know where to go and then kind of, how to judge whether what you originally planned for was accomplished." [person F]*

Future value, as described by the participants focused on use of the learning beyond the learning:

> *"…make it stick better or make it mean more instead of just reading to memorize or learning to get through a class, but to actually be able to recall it as useful information and be able to use it in some kind of application or other context later on." [person X]*
>
> *Or:*
>
> *"…more importantly than just learn it, you need to retain it and you do that by repetition, practices. And then at the end of the day you can go up to anyone and explain exactly what you just learned in a way that you're*

> *comfortable doing it and saying it in an almost speaking voice." [person H]*

The Stolk attributes which most closely align are in the monitoring/control phase and cognition area where monitoring of cognition and metacognitive awareness are placed. The concept of making use of specific retention activities to "make it stick better" is not explicit in the Stolk framework.

<u>*Motivation/initiative*</u> is a "way of experiencing" for the participants of this study. Motivation is an area of self-direction (row) in Stolk's framework and intention is a phase (column). The descriptions by students align with descriptors in both the column and the row: need recognition, desire for growth, choice to engage, goal orientation, awareness of interests:

> *"...you have the skills and ability to recognize when you need to know more than you currently do or you have a desire to and you take the initiative to find ways to learn it…"[person E] "…means having the motivation to be able to obtain the resources that you need to be able to achieve a certain goal." [person L]*

<u>*Efficiency/effectiveness*</u> is represented in Stolk's framework in the reflection/reaction phase through descriptors like self-evaluation of performance and outcomes, self-evaluation of efforts and actions, evaluation of task demands.

> *"You develop a set of skills to where you learn an efficient process that helps you acquire new knowledge at a faster rate than you normally would." [person 16]*
>
> *"finding your own pattern of how you learn effectively and then continuing to use it and if there's any extra like key things that you learn along the way, you kind of learn how other people learn more effectively and maybe that worked for you, so you pick up some ideas from them." [person 2]*

This phase of the phenomenography is intended to compare and contrast the different ways the participants experience self-directed learning. Through aligning the categories of SDL experienced with the theories identified in Chapter 5 and with the prior work done by other researchers, the similarities, and differences of these categories have been highlighted.

9.4. HIERARCHY

The categories of the ways PBL graduates experience self-directed learning are perspectives, lenses through which the people view their own learning, rather than steps they actually take during the learning. This step in a phenomenography is meant to create a hierarchy based on the significance of the categories. In the Chapter 2 discussions on learning theory, Illeris' triangle, and the APA learner centered psychological principles served as models for characterizing learning. The ways PBL students experience self-directed learning can be viewed through the perspectives of these models. Figure 9.2 provides context for viewing how students who have completed a PBL curriculum experience self-directed learning.

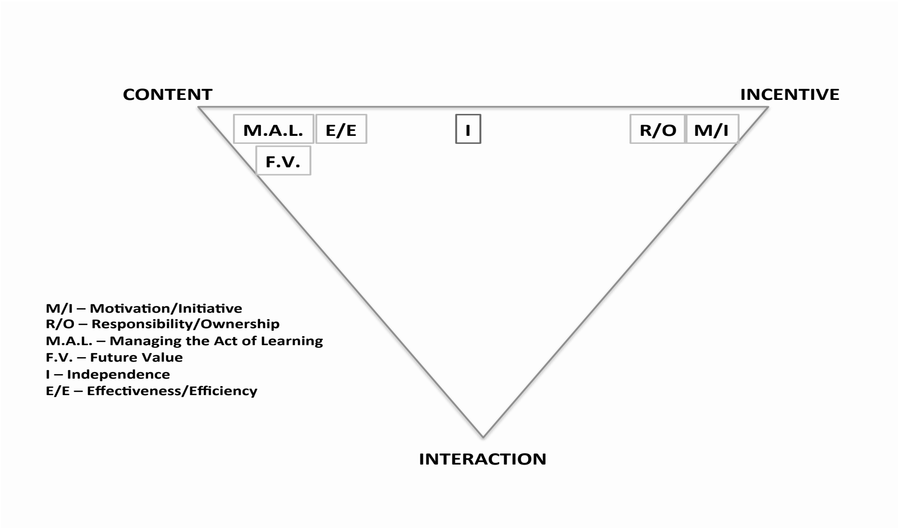

Figure 9.2. Placement of the ways PBL students experience self-directed learning on Illeris Triangle.

The APA principles serve to complement these placements. Figure 9.3 is a condensed version of Figure 2.14 to be used for reference in this section. Both the APA principles and the Illeris framework shed light on the characteristics of this perspective of the student PBL experience.

Cognitive and Metacognitive Factors

1. **Nature of the learning process**
2. **Goals of the learning process**
3. **Construction of knowledge**
4. **Strategic thinking**
5. **Thinking about thinking**
6. **Context of learning**

Motivational and Affective Factors

7. Motivational and emotional influences on learning

8. Intrinsic motivation to learn

9. Effects of motivation on effort

Developmental and Social Factors

10. Developmental influences on learning

11. Social influences on learning

Figure 9.3. American Psychological Associate Learner-Centered Psychological Principles (APA, 1997)

Following is a category by category description of how the "ways of experiencing" align with APA (1997) and Illeris (2007).

Motivation/initiative

The APA principles applicable to motivation are 7 and 8: *motivational and emotional influences on learning* – what and how much is learned is influenced by motivation, intrinsic motivation to learn – *intrinsic motivation* is stimulated by tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control, and *effects of motivation on effort* - without learners' motivation to learn, the willingness to exert this effort is unlikely without coercion. This places motivation in the incentive corner of Illeris' triangle (see figure 9.2).

> *"…you have the skills and ability to recognize when you need to know more than you currently do or you have a desire to and you take the initiative to find ways to learn it, and you don't like expect someone to hand you the training you need to go to or tell you [that] you need to do something or read this book or take it upon yourself to ask questions." [person C]*

Responsibility/ownership

The APA principles most applicable are again the motivational and affective factors. In particular, principles 7 and 9: *motivational and emotional influences on learning* – motivation to learn, in turn, is influenced by the individual's emotional states, beliefs, interests and goals, and habits of thinking, *effects of motivation on effort* - acquisition of complex knowledge and skills requires extended learner effort. Responsibility/ownership is thus placed in the incentive corner of the Illeris triangle (figure 9.2).

> *"…taking control of your own learning and knowing that you're responsible for what you want to accomplish and taking that ownership and then forming your own plan for the direction that you want within your learning." [person AB]*

Managing the act of learning

The cognitive and metacognitive factors from the APA principles align with *managing the act of learning* category. In particular, principles 1-5: *nature of the learning process, goals of the learning process, construction of knowledge, strategic thinking, and thinking about thinking* align well. These principles are positioned in the content vertex of the Illeris triangle (figure 9.2).

> *"The ability to look at a situation that you might not necessarily know the competence or the components that go into it and be able to analyze it and break down into the components what makes up that situation. At that point, you can then go research those components, learn about them in a way either completely on your own or by seeking individuals that have competence, have already learned those subjects and then being able to take that knowledge that you've gained and apply it back to that situation." [person Y]*

Future value

Future value, like *managing the act of learning* aligns with cognitive factors. The *goals of the learning process* – the successful learner, over time and with support and instructional guidance, can create meaningful, coherent representations of knowledge; *construction of knowledge* – the successful learner can link new information with existing knowledge in meaningful ways; and *strategic thinking* – the successful learner can create and use a repertoire of thinking and reasoning strategies to achieve complex learning goals, are all ways in which the learners are positioning their learning for future value beyond the learning activities. The future value has a content orientation in the Illeris triangle (figure 9.2).

> *"…it's the ability to pinpoint what exactly you need to learn, so you first identify the thing you need to learn. Then you go forth in some manner that you know you can learn that and you take your time with it and you learn the information. But more importantly than just learn it, you need to retain it and you do that by repetition, practices. And then at the end of the day you can go up to anyone and explain exactly what you just learned in a way that you're comfortable doing it and saying it in an almost speaking voice." [person E]*

Independence

The *independence* way of experiencing can be viewed as rather isolationist. Though some of these participants acknowledged interacting with others as resources or to receive feedback, they mostly experienced self-directed learning as a non-social activity. This independence does not align with the APA principles, nor a positive position in the Illeris framework. Rather, it is a counter example to principle 11: *social influences on learning* – learning is influenced by social interactions, interpersonal relations, and communication with others. For placement in the Illeris framework, it will be positioned opposite from the social interaction vertex (figure 9.2).

> "…being able to find, whether through some sort of motivation to go out and learn basically on your own with very little involvement from an instructor or an outside source." [person N]

<u>*Effectiveness/efficiency*</u>

Effectiveness/efficiency again aligns with the cognitive APA factors in the content corner of the Illeris triangle (figure 9.2): *nature of the learning process* – the learning of complex subject matter is most effective when it is an intentional process of constructing meaning from information and experience; and *strategic thinking* – the successful learner can create and use a repertoire of thinking and reasoning strategies to achieve complex learning goals.

> *"You develop a set of skills to where you learn an efficient process that helps you acquire new knowledge at a faster rate than you normally would." [person P]*

In summary, academic staff and curriculum designers looking to implement PBL can use the results of this perspective to both embrace what these results tend to indicate and to address the missing elements and placements. It is important to note that the nature of this analysis forced a primary classification decision. Students exhibited characteristics across multiple categories. But for this analysis, their strongest indication was chosen. Thus, the individuals themselves are not to be considered as singularly dimensional. As a group, the characterization is fully along the top of the Illeris triangle. The dimensions of experience run the continuum from content to incentive. The APA principles addressed on this continuum are number 1, 2, 3, 4, 5, 7, 8, and 9. These results could be of value to address how PBL models can address these important principles of learning. Just as importantly, these results can indicate what principles of learning may be missing or may be tacit to the learners. The missing principles are 6, 10, and 11:

6. *Context of learning* – Learning is influenced by environmental factors, including culture, technology, and instructional practices.
10. *Developmental influences on learning* – As individuals develop, there are different opportunities and constraints for learning. Learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account.
11. *Social influences on learning – Learning is influenced by social interactions, interpersonal relations, and communication with others.*

While, what participants address does come from the internal interactions leg of Illeris triangle, the external interaction dimension is missing. Participants did not address these external factors in their personal models of self-directed learning. Their environment, social interactions, and their individual development was not addressed. Again, this could be viewed as having been either tacit or non-existent.

With this knowledge, curriculum developers and academic staff can contemplate how PBL learning experiences can be developed to increase value to students by addressing these areas of learning.

9.5. CONCLUSION

The goal of this chapter was to complete the phenomenography by identifying the outcome space showing the differing ways that PBL students experience self-directed learning. This model was identified in figure 9.1. The direct quotes of the PBL graduates and the theoretical perspectives presented in previous chapters were used to explain the differing student experiences, create structure within the "ways", and create boundaries between them. Understanding how PBL students experience SDL has potential value for curriculum decision makers. Specifically, by looking at what learning attributes resulted in the sophisticated ways of experiencing. Further, looking at the existence of the novice ways of experiencing, developers can design activities to build more sophistication and activities to improve the novice experiences.

***FINDING # 3* – Phenomenographic Model. The qualitative study has resulted in a phenomenographic "outcome space" that can be of value to understanding how PBL students experience self-directed learning. This understanding is a key perspective to be considered when implementing new PBL models or the contemplation of implementing PBL in engineering education.**

CHAPTER 10. COMPOSITE MODEL

When the qualitative study was initially designed, it was expected that the only result would be the phenomenographic outcome space. However, emerging from the first and second readings came a composite model of how the PBL students interpreted and implemented self-directed learning. What emerged were the elements they use and the processes they use to combine the elements. This is different than how they experienced SDL as was portrayed in Chapter 9. This composite model is a new perspective, which is composed of the SDL elements the PBL participants described. The flow of the model comes from the ways the participants described the interactions of the elements as they implement SDL in their engineering work. They frequently described a cyclical nature of their learning and an intermittent monitoring. This model is included as a result of the qualitative study since it too provides perspective on self-directed learning development of PBL engineering students. In this chapter, the model is developed, using the words of the participants, the way it emerged in the transcript readings. The model is illustrated in Figure 10.1.

Using only the language of the participants, each component of the model is described below.

10.1. DEVELOPMENT OF MODEL FROM PARTICIPANT RESPONSES

<u>Acknowledge motivation</u>

> *"I need to have a need in my life to learn something. I think it's just completely stupid, I think, for me it's completely stupid to learn something if I'm never going to profit from it or use it or have an economic reason or it's not going to make me a nicer person or something like that. So I had a really hard time, I always thought it was stupid how in math we'd learn these things, you know, in the calc sequence and I don't remember them, because there was no need for me to remember them. I'm not going to feel guilty about how I don't remember them, because I never use it, you know. ... So that was like, I guess an example of when metacognition like helps me kind of zero in on a way that I was actually able to learn new things and be excited about it enough to you know make it, to put myself in a position where I was willing to do the work to learn something." [person X]*

Set goals/objectives

> *"First, you identify your knowns and unknowns, come up with the set of things, your goals." [person P]*

> *"…so the first step, I think, is deciding what you want, what is basically, the large field you are looking to gain knowledge in. The next step is determining what you don't know about it, determine what you want to know specifically about it and kind of try to break it down from the big unknown, and then deciding which way to attack the problem." [person V]*

Plan/schedule

> *"… come up with a plan and identify your resources, how much time you're going to spend, etc. then carry out the plan…" [person P]*

> *"…you create a schedule, goals, a to-do list, even though you have a master schedule, you have to do this. That's daily. And then execute your goals. Make sure they're done…. Then, you go through the same process again cause sometimes you cannot achieve, well, sometimes you can say a certain period of time and surely you can't finish that certain period of time because things, you know that things are coming from all over I mean. Anything can happen, so, you go back and analyze, why didn't this finish during that period of time. Will I be able to finish it? Set up goals again and try to achieve it." [person Q]*

Activate prior knowledge

> *"…started reading a little deeper into those and by getting deeper into those resources they led to a lot of different resources on different levels and that knowledge, a lot of it, tied back to prior knowledge that I had from different courses, so it was necessary, I guess to tie some of that back and maybe to look up some concepts of past classes, just to refresh what was there, so it tied into some other things." [person L]*

Seek resources

> *"… then I started researching resources that might have some help into that, found some books and online resources and a few different things … started reading a little deeper into those and by getting deeper into those resources they led to a lot of different resources on different levels and that knowledge…" [person L]*

> *"…my learning source is talking with people that I know. Like, it's the network of people that have the knowledge more so." [person H]*

Learning activity - create model

> *"And then I would go through the process. I would gain whatever knowledge I can and whatever I don't know." [person V]*
>
> *"So once I'm able to find out who or all of the resources that I would need, it's just kind of zeroing in... In my method, I just like to start, I need to kind of go sequentially almost and I know for a lot of people they can start from different angles or from different points, but for me, I just need that, I need that foundational support because, I ask myself well, how does this work, how did this come about, what's the underlying principle. Then I can start working my way to getting probably exactly what I would need to get." [person N]*

Seek feedback

> *"And then once, let's say you learned it, then that's when you kind of go for the final, did I actually learn it? It's kind of another feedback step, but it's more defined. There should be feedback in everything, but this one is more, kind of understand what you got and if that doesn't work then you kind of backtrack and work your way through the other steps." [person F]*

Elaborate on model

> *"I would make sure and come back through the process and figure out what I'm missing, why I missed it, and keep going through, and I think keeping reflection in that." [person V]*

Practice retention activities

> *"…and then you possibly reflect on it later to insure the knowledge sticks. So some sort of using the knowledge in the future…this knowledge might be relied upon on the next endeavor." [person V]*

Document

"Once you find [the information], you collect it, document it, typically you'd want to document it." [person V]

> *"I found out that in that moment what was crucial is the writing down portion of retaining it, 'cause if you need to learn, you need to retain it. And for me, writing down really anything helped retain it. I remember I still got books, just pages, written about the cardiovascular system, and that was a really crucial moment on really every step of the way it is, that*

was my way for remembering and retaining it, was going over it, talking to someone and then writing it down to verify. It seemed after I wrote it down, I knew it, you know. Like, I never needed to look back at those notes. I could open up a book and look at the page and I'll be able to tell you everything I wrote in there." [person E]

<u>Monitor (efficiency, effort, alignment, schedule, personal attitude)</u>

"So what I learned to do is that if something doesn't seem like it is going to give me any valuable information, I just kind of omit that research or those results and just say, don't spend any more time on it because it's not adding any value to my learning or my time I'm using up…Yeah, so obviously time is valuable, so if in the first five, ten minutes of reading something I don't think it's valuable or adding anything to it, I'll just skip it and go on…" [person M]

"Depending on how easy it was or how you feel you know it afterwards will decide if you want to continue learning it more on your own or if you want to seek outside resources… before you continue further down the path." [person P]

"I would go through and evaluate which techniques, which resources that I have had or have at the moment would be able to facilitate that knowledge gain faster, more efficient." [person V]

"I've been continually monitoring where I'm at with self efficacy. And I haven't seen that much of a growth in that area, but what I have seen is a huge growth in like where I attribute my learning to because, I didn't really have a good idea of where I was as far as whether I attributed my learning to myself or to others, so I guess my growth isn't so much toward one end or the other of the spectrum, but it's just being aware of where I can get my learning from and where to put the responsibility at. I mean ultimately it's on myself, but if I have a good resource to go to for a teacher, seek that out, but if you don't, then don't just wait around for someone to tell you what you should be doing." [person AB]

<u>Verify/evaluate</u>

"…evaluating, you know when we finish a project, evaluating how our work was, how effective it was, it's usually lately for us, it's been kind of process stuff, like how do we get our gear into a place and how do we get it out efficiently and how do we, you know, sometimes you're in the most boring parts of our processes can take a lot of refining, but reevaluation or like evaluation once you're done with a project is huge." [person X]

Regulate for future

> *"…the next time I have to do one, well, what did I do last time? What can I do differently? What other tools can I use instead? … looking back to what you did and seeing if it worked, do it again. If it didn't work, great, maybe improve it or if it didn't work at all, maybe look completely different, to do it in a different way." [person M]*

10.2. COMPOSITE MODEL DESCRIPTION

Figure 10.1 is a graphic interpretation of the SDL elements described above by the interview participants. In this composite model, the initiation of learning begins with *acknowledgement of a motivation* to learn and a sense that without that motivation, the learning need not proceed. As with most of the elements of the model, for some participants this acknowledgement was explicit, while some just implied it, and for others it was tacit. The next steps were to *set goals* and *make plans and timelines* for the learning. At this point in the model, the learner enters a cycle that has 8 distinct stages: *activate prior knowledge*, *seek resources* (media or person), *create a conceptual model* while in the act of "doing" the learning, *seek feedback*, *elaborate the model*, *practice retention activities* to make the model stick, and *verify/evaluate* the model.

While in this model, the learner *monitors* several aspects of her learning, just as a driver might monitor her speed, fuel level, oil pressure, distance traveled, etc. on the dashboard of her car. When the driver notices the speed is too high she slows down. When the fuel is low, she changes route and seeks a fuel station. When she has traveled a certain distance, she looks for the appropriate turn on another road. Similarly, the learner is also monitoring a "**dashboard**." She checks to ensure her *effort* and *work efficiency* are at desired levels. She checks to ensure that the work she is doing is *aligned with the goals* she set. She monitors her *satisfaction* with the learning process, and she compares her progress with the *timelines*. Just as with the driver, when the dashboard indicates a need, she may make adjustments to the timeline, plan, or goals. She may decide to exit the learning cycle. Or, she may use this input to revisit one of the stages of the cycle for further work. For example, a learner, who is working in the creation of the conceptual model and "checks the dashboard" to see that there is misalignment between the current model and the learning goals, may cycle back to seek more resources.

Many of the interview participants identified the cyclic nature of their learning, expressing that they would go through steps multiple times, advancing the sophistication of their learning until they were satisfied. Thus, the model has curved arrows showing that returning to one or several stages is an option at the end of each stage. Further, they identified the need for documentation in nearly all stages

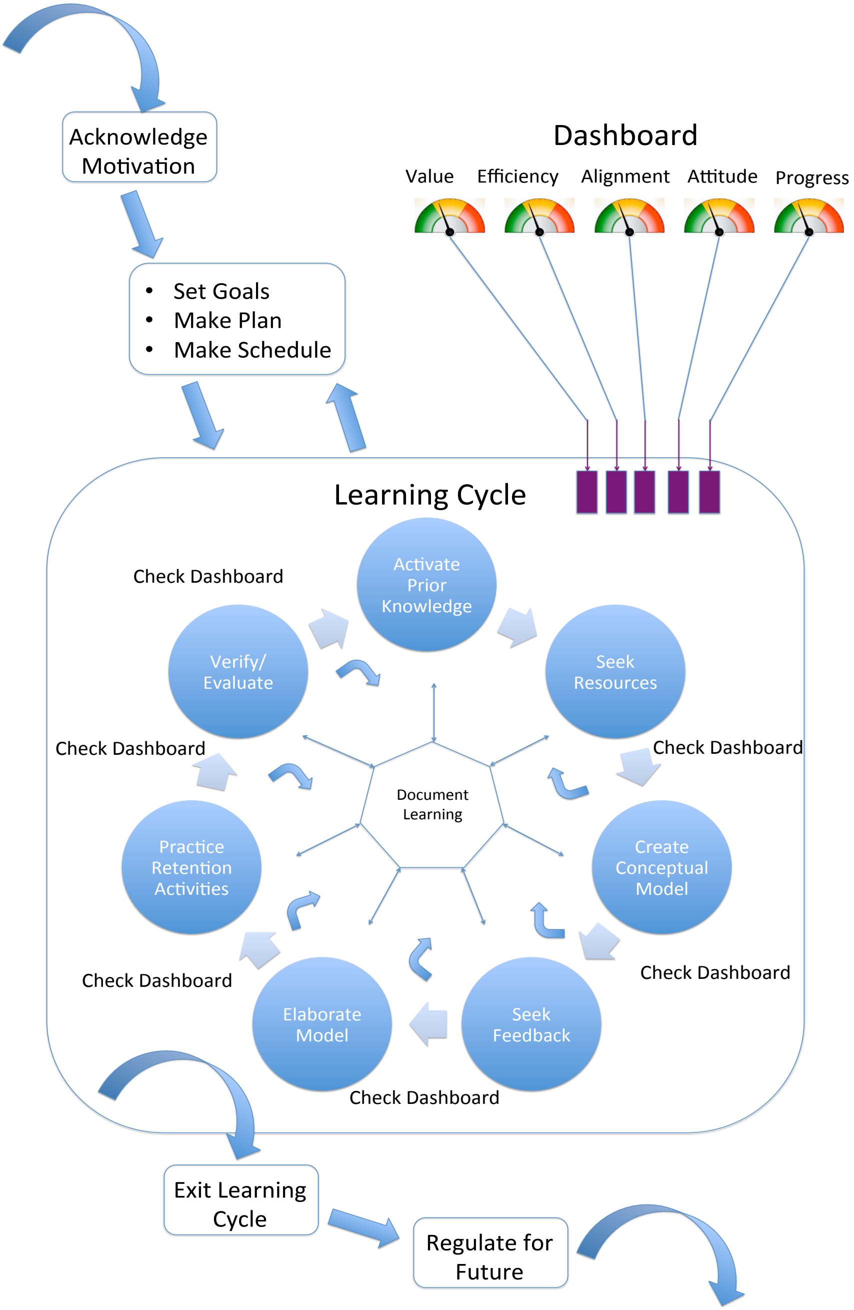

Figure 10.1. Composite model of self-directed learning experienced by PBL graduate

of their learning cycle. This put documentation in the center of the learning cycle to be recorded, as appropriate, by the learner.

There is no distinct place in the cycle to exit. The learning cycle ends when the learner has reached an appropriate level of satisfaction or dissatisfaction or has exhausted the time available. A learner may have gone around the cycle many times or, perhaps, only partly around. Upon exiting the cycle, the learner may take the opportunity to reflect on the learning processes that were used and regulate for future learning.

To further clarify, this is a composite model. No one learner explicitly identified all of the stages in this model. Rather, it is an interpretation of how learners described the different aspects of their learning, how they moved from one stage to another, how they monitored their learning while it was happening, and how they reacted to the results of that monitoring.

10.3. ANALYSIS OF COMPOSITE MODEL

In Chapter 9, the phenomenographic "ways of experiencing" were classified using the Illeris framework and the APA principles. This current section is concerned with performing a similar analysis on the composite model. While the "ways of experiencing" model can provide value for people considering how PBL implementation impacts students' perspectives, and how instruction may address those perspectives, the composite perspective may serve as a model to be used in instruction or for individuals looking to explicitly perform self-directed learning. This analysis can serve to find missing elements in the SDL model experienced by this PBL participant group and make suggestions for improving the model. Following are the components placed on the Illeris framework, each of the APA principles applicable to models of learning (1-11), analysis of how the various aspects of the composite model identify with the principle, and potential improvements to the composite model based on the principles.

10.3.1. ILLERIS TRIANGLE PLACEMENT OF COMPOSITE MODEL ELEMENTS

Figure 10.2 below has each of the aspects of this composite model shown on the Illeris framework. The similarity to the placement of the "ways of experiencing" on this 2D continuum is the distribution between content and incentive. The majority of activities are cognitive/metacognitive and placed towards the content vertex. The act of monitoring using the "dashboard" leans towards incentive. In this model, there is interaction as the learner seeks people resources, feedback, and validation. This graphic shows there may still be remaining need for more interaction.

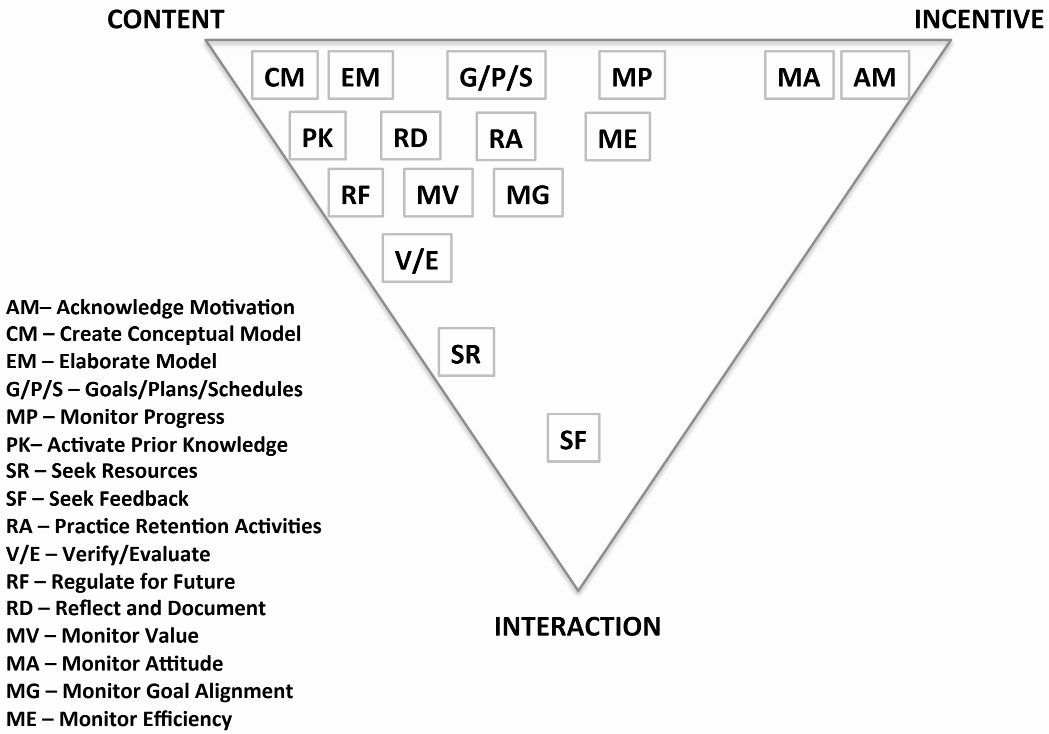

Figure 10.2. Placement of Composite SDL model elements on Illeris Triangle

10.3.2. APA LEARNER-CENTERED PSYCHOLOGICAL PRINCIPLES AND COMPOSITE SDL MODEL

1. Nature of the learning process – The explicit act of using a model like this is what makes the process intentional for the learner. The model elements most aligned with this principle are *acknowledge motivation, create conceptual model, and elaborate on model.*

> *"For myself, just being able to use (SDL), being able to take advantage of any kind of learning experience that I can get ahold of. If it's something that I want to know about or if it's something that I need to know about, I can say with confidence to my boss or to myself, yeah, I can figure that out. Give me some time. It will take x amount of time probably, but I can figure that out. It can be done." [person A].*

> *"…it's building up the knowledge that you need to get to that situation. From learning in these different areas, that's when the application begins. You begin putting all this information together and seeing if there're any gaps to what knowledge you've gained, to what you need to apply to that situation. And this is analogous to the plan-do-check-act method used heavily in manufacturing." [person Y]*

2. Goals of the learning process – The acts of *setting goals and making plans and schedules* enable the learner to strive for and *monitor progress* towards meaningful representations of their knowledge.

> *"…like I said, the front end of it was, I wrote down a list of things, different takeaways, that I really wanted and wanted to understand more deeply and kind of even broke those down into what I thought I could understand about those." [person L]*

> *"So, once you define it, then that's kind of when it kind of goes into the planning stage to where you define, when you're going to learn it, so like resources and like the medium, whether it's whatever source that it may come from and then also kind of planning, I don't know how to say it I guess, but kind of go back to how you're going to use a plan, like I'm going to learn this much, so I can use it this much." [person F]*

> *"That's kind of like how I came up with the fact that I was having a problem, so I was monitoring my learning, my progress in that way and then, so I have a problem, what is the problem and then how can I solve the problem." [person B]*

3. Construction of knowledge – The learner *activates prior knowledge* and *seeks resources* to link new information with existing knowledge in meaningful ways when creating a *conceptual model*.

> *"Get a good idea of vocabulary, key words that are used and see what it's related to, be able to understand what types of subjects are associated with it to get a good idea of what exactly I'm expected or required to learn. Once I've done that, if I can explain it or relate it, so this is like fluids, for example, this is like Archimedes principle, or you could just name some other physics law that relates to it and then build from there." [person T]*

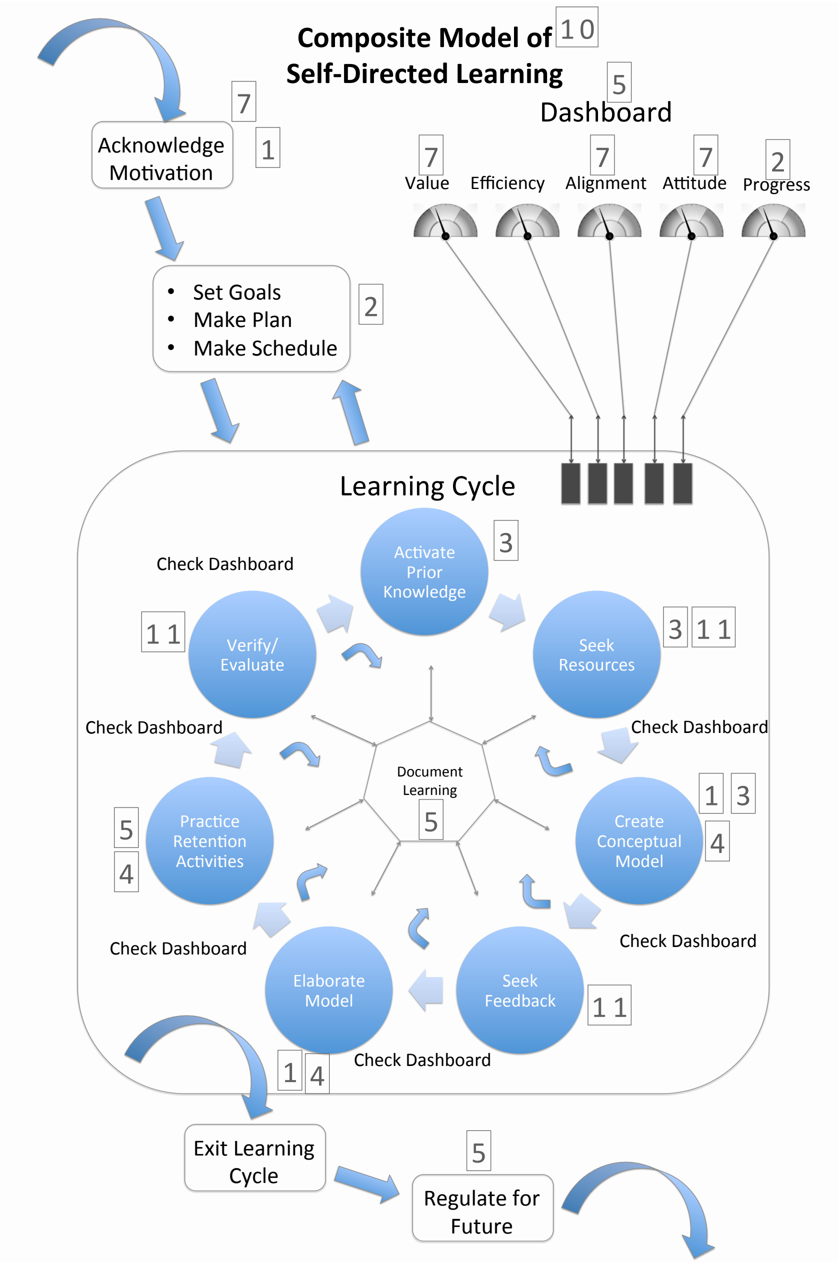

Figure 10.3. Placement of APA principles on composite SDL model

> *"And the different activities were researching and books, watching videos, talking with other people. I think those were the main three… a cycle between those three, read books, watch videos, write down your knowledge." [person E]*

4. Strategic thinking – To achieve complex learning goals, the learner uses thinking and reasoning strategies while *creating and elaborating* their *conceptual model.* These strategies extend to the encoding the learner performs while *practicing retention activities.*

> *"So I'd kind of reflect back at night and then wake up in the morning and go back and open up to the pages that I said I needed to study more and then just like from what people told me the day before and bring it over to the new pages and go back and reflect on the old pages." [person R]*

> *"…the past job I had, I had an hour ride home everyday. That hour ride home, that was just a time to think, go through a lot of things, and I think that's where some of the best growth actually happened. When you have that time to just kind of reflect on what you did during the day and what worked well and what happened." [person L]*

5. Thinking about thinking – Through intentional reflection, the learner performs metacognitive activities while *documenting learning*, *practicing retention activities* and *regulating for future learning*. Further, any act of monitoring the learning during learning is metacognitive. Thus, checking the "dashboard", and any regulation that comes from the checking is also thinking about thinking.

> *"…adding in a check for how am I progressing through this objective, or to this objective, what's going well, what's not going well, what can I change to improve this learning. So I guess during the actual implementation of learning between finding resources, making a plan, implementing it, there's the monitoring that is a continual loop." [person I]*

> *"…reevaluation or like evaluation once you're done with a project is huge. I think to keep that state of growth, and like ask the questions that you don't have answers to yet, like how can we be more efficient or how can we do a better job." [person X]*

> *"I mean you might have learned what you needed to, but I mean you could still probably improve the process and I think that's kind of part of what the metacognition is." [person F]*

6. Context of learning – Missing, in the composite model created as participants described self-directed learning and their implementation of it, was the management of and interaction with environmental factors. The model can be improved by accounting for these contexts.

7. Motivational and emotional influences on learning – The composite model acknowledges motivation and monitors value, goal alignment, and personal attitude. An explicit monitoring of motivation could strengthen the model.

> *"I think because my personal attitude towards it was that I enjoyed it. I enjoyed learning about it. I enjoyed the aspects of the classes. That I had more ambition, more willingness to go and learn it than when, for example, I really didn't have the ambition or attitude to really learn the electrical, the electrical classes that we had, and then I'd kind of realize that I learned better when I was more interested and that gave my personal attitude, my personal thoughts were more like, this should be fun. I need to learn this. There's something in here that will benefit me. That learning was better so I ended up transferring that into my electrical classes and I realized and I saw the difference because, beforehand, my first time it was just like, this was just stuff I needed to get my degree and I didn't too well in my class. Then I realized well, what's the difference between that and the fluids and it was all about the attitude. I changed my attitude for my next one and I saw better connections to what I was learning and being able to relate it to other aspects that I was learning because one of my biggest connections is that electrical circuits can be viewed as a fluid system. Your resistances, your flows, voltages, currents, and all that, you can put them back and forth, and for me that helped because I took an electrical system, turned it to a fluid system, and I could see what was going on." [person K]*

8. Intrinsic motivation to learn – Intrinsic motivation factors, as described by the APA, include: "tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control." This is connected to Deci and Ryan's (2000) self-determination theory as described in Section 5.1 where competence, connectedness, and autonomy are shown to impact motivation to learn. The composite model, accounting for the *monitoring of motivation and attitude,* partly addresses these contributing factors to intrinsic motivation, though a more explicit monitoring of difficulty may expand the sophistication of the model.

> *"Depending on how easy it was, or how you feel you know it afterwards will decide if you want to continue learning it more on your own or if you want to seek outside resources… before you continue further down the path."* [person P]

> *"I've been continually monitoring where I'm at with self efficacy. And I haven't seen that much of a growth in that area, but what I have seen is a huge growth in where I attribute my learning to because, I didn't really have a good idea of where I was at as far as whether I attributed my learning to myself or to others, so I guess my growth isn't so much toward one end or the other of the spectrum, but it's just being aware of where I can get my learning from and where to put the responsibility at. I mean ultimately it's on myself, but if I have a good resource to go to for a teacher, seek that out, but if you don't then don't just wait around for someone to tell you what you should be doing." [person AB]*

9. Effects of motivation on effort – Self-monitoring of effort was not addressed by the participants, but would be an improvement to the composite model.

10. Developmental influences on learning – From the APA, "learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account." The differential developmental influences are inherent in the entire composite model. The focus on the model is self and how the individual can choose to use her own path through learning. This is based on her level of development, on her interaction with the attributes of the learning process, and her own satisfaction with and motivation for learning.

> *"…the first thing is having an objective, so something that you need to learn or a goal or I guess what you want to learn. And then finding out, I guess the background information or a starting point for what you're trying to learn and I guess unknown unknowns would be bad, so finding out what you don't know because it's hard to learn something if you don't know what you don't know. And then coming up with some strategy or plan to learn the information, whether it's an online course, through an instructor, asking a question or a coworker who knows, then finding a resource and then carrying out. I guess it is a post-learning, figuring out that you know it correctly and you didn't learn it wrong is probably important and then identifying if there's still things that you don't know and if you need to learn those things as well or where you're going to go in the future, or if you have enough information for what you're looking for." [person I]*

11. Social influences on learning – The composite model, as described by participants, accounted for interactions with others as the learner *seeks people resources, seeks feedback, and performs verification/evaluation*. While the participants acknowledged these connections, they did not acknowledge the importance of social interactions in the learning process, nor did they consider monitoring the social aspects of learning. The model could be improved by adding a monitoring of social interactions in the "dashboard."

> *"…then, if I do keep getting stuck there, I will go find help because self-directed learning that I've learned over the years isn't always by yourself. It is something that if you do get caught up, you need to find somebody who has more experience in that area than you, someone who can help you"* [person R]

> *"I would also check in with my boss to make sure I'm actually going on the right path, so keeping focus."* [person V]

> *"So I always try to have it reviewed by a peer before I go to actually give the final results, make sure my work's to a T, correct and then either through a presentation or single values or whatever have you go to the final audience."* [person Z]

> *"…was going over it, talking to someone and then writing it down to verify. It seemed after I wrote it down I knew it, you know… And that's really kind of the final step and the validation, of course, was talking to Dr. Dan."* [person E]

The purpose of this section has been to analyze the composite PBL model experienced by the participants as framed through the perspectives of learning. The results show how the model fits on the tensions between cognition <-> incentive and cognition <-> interaction. The self-directed learning model leans toward cognition, as perhaps it should. SDL is a component of the overall PBL model focused on the individual learning of technical content, which is a highly cognitive endeavor. The other aspects of the PBL model, such as design and professional learning, as described in Chapter 4, show how the overall PBL engineering learning experience does provide more balance towards incentive and interaction.

Further, the composite PBL model was analyzed as viewed through the 11 aspects of learner-centered principles. Each element of the model was connected to one or more of the principles, as shown in Figure 10.3. However, there were aspects of the learner-centered principles that were not indicated in the model. These are managing and monitoring interaction within environmental contexts, as well as explicit monitoring of motivation, difficulty, effort, and social interactions on the dashboard. To use the model for potential development of students' SDL skills, these improvements could be made.

10.4. CONCLUSION

From the literature, Hmelo-Silver (2004) identified essential sub-skills of SDL. They are the following: metacognitive awareness of what is and is not understood, an ability to set goals, identification of what more needs to be learned, ability to plan learning and select appropriate learning strategies, and monitoring and evaluating goal attainment. The composite model developed in this chapter clearly demonstrates that the PBL students exhibited these essential sub-skills. A sub-goal of this PhD study was to identify the SDL elements that PBL students develop and the levels to which they are developed. The composite model identifies these elements and the above analysis details the levels of sophistication.

FINDING #4 ***- Composite Model of SDL. Through the descriptions of how they implement self-directed learning, PBL participants identified a broad set of elements and processes. The interpretation of these resulted in a model of SDL that provides an added perspective to be contemplated. Further, this model has the potential to be used by facilitators looking to guide SDL development of students or by individuals looking to improve their own SDL abilities.***

CHAPTER 11. CONCLUSIONS AND FINAL REFLECTIONS

Through the completion of this research study, four findings have been identified. The complete description of the findings is presented in figure 11.1 below. Presented in this final chapter are a review of the initial intent/motivations of the PhD study, a summary of work completed, a discussion on the research questions, statements on contribution to the state of the art, lessons learned, critiques of the work completed, future work, and a final statement on PBL.

FINDING # 1 – Quantitative Result. Confirmation of expectation from theory and literature that PBL engineering students develop as self-directed learners during engineering education whereas traditional engineering students do not.

FINDING #2 – Level of Sophistication of Self-Directed Learning. Emerging from the qualitative study is a view of how PBL graduates identify, view, and use the elements of self-directed learning. PBL students identify 15 SDL elements. On average, they use more than 2/3 of the identified aspects. Highly utilized SDL aspects are "goal setting", "performing learning activities", "verifying results", and "seeking resources." The underutilized element of SDL is "considering the next step in learning."

FINDING # 3 – Phenomenographic Model. The qualitative study has resulted in a phenomenographic "outcome space" that can be of value to understanding the various ways PBL students experience self-directed learning. This understanding is a key perspective to be considered when implementing new PBL models or the contemplation of implementing PBL in engineering education.

FINDING #4 – Composite Model of SDL. Through the descriptions of how they implement self-directed learning, PBL participants identified a broad set of elements and processes. The interpretation of these resulted in a model of SDL that provides an added perspective. This model has the potential to be used by facilitators looking to guide SDL development of students or by individuals looking to improve their own SDL abilities.

Figure 11.1. Research study findings

11.1. REVIEW OF ORIGINAL INTENTIONS

In volume 1, the many attributes of the Iron Range Engineering PBL model were detailed. There are a variety of research areas that emerge from the details of what Iron Range Engineering is and how it is delivered as a curriculum. From the many potential research areas, self-directed learning was selected for this PhD study. It is common understanding among engineers that most of the technical knowledge they need in practice is acquired after college. This makes the ability to acquire that knowledge oneself an important skill. During 25 years in engineering education, I observed little attention being paid to empowering students to become better self-directed learners. These observations and beliefs served as the motivation to study the impacts of PBL on the development of self-directed learning abilities.

The intent of this work was to provide engineering education curriculum decision-makers with descriptive data to consider when making curricular decisions. A research study was designed to answer the main research question "How do PBL students experience self-directed learning?". In this question, the word "experience" is used broadly to cover the development of SDL readiness, understanding of SDL, and utilization of SDL elements. As described in Chapter 6, a constructionist epistemological approach using an interpretivist, situational perspective was taken. The research was carried out on a group in a specific social context. I was a member of that social construct. The goal was to characterize the details of self-directed learning in this context and make them available to others to contemplate in their different social contexts.

11.2. SUMMARY OF WORK COMPLETED

As stated above, the work was undertaken in the following three parts: review of the literature (Chapter 5), quantitative study (Chapter 7), and qualitative study (Chapters 8, 9, 10).

11.2.1. THEORETICAL PERSPECTIVE FROM THE LITERATURE

Chapter 5 was dedicated to literature review. First, a description of what self-directed learning is and how it relates to metacognition, lifelong learning, self-determination theory, self-regulated learning, and PBL was presented. Then, from the literature, the previous studies of self-directed learning and project-based learning were described.

The overall research question emerged from the review of literature. Understanding how PBL students experience self-directed learning leads to the intended outcome of having valuable information for curriculum decision makers to consider. The study of metacognition, self-regulated learning, lifelong learning, and self-directed learning was valuable. They have details that added much to the ability to understand learning at deeper levels. The conclusion is that all together they support the actions in self-directed learning. Further, the attempts at defining their boundaries became useful in establishing the boundaries for the ways of experiencing that resulted in the outcome space of the phenomenography. A study on the previous works of others resulted in the following conclusions:

1. Self-directed learning has become a highly valued outcome of engineering education.

2. There is a pattern of quantitative research indicating that a traditional engineering education results in little, if any, development of self-directed learning abilities.

3. There is a pattern of research that indicates project-based learning can result in SDL development.

4. Guglielmino's self-directed learning readiness scale (SDLRS) has been validated and widely used to measure self-directed learning readiness.

5. SDLRS results need not be paired pre- to post- to be valid.

6. The SDLRS can be used to predict success in PBL.

7. Considering the importance, little work has been done to understand *how* engineering students develop as self-directed learners.

8. Nearly all works reported in the literature on self-directed learning are quantitative in nature (Chapter 5).

The previous works by other researchers confirm that SDL is undervalued and understudied in engineering education. Their works set a stage for believing that PBL results in better development of self-directed learning and that the SDLRS is a reasonable tool for quantitatively analyzing self-directed learning abilities. This information was critical to enable the design of the quantitative study, and more so, to justify the need to answer the research questions.

Of tremendous value from the literature review, was the contribution of self-determination theory to this study. This work by Deci and Ryan provided a lens through which a person's motivation to learn can be explained. Understanding how levels of autonomy, competence, and connectedness impact a person's motivation can explain how PBL results in greater self-directedness in learning. PBL, by its design, provides students more autonomy and connectedness than traditional learning.

Thus, a stage had been set. Self-directed learning was defined and placed with respect to learning and motivation theories. The works of others indicated the value of SDL in engineering education and its development with respect to PBL and non-PBL environments. An instrument for measuring SDL was identified and validated.

The need for further work in studying SDL development in PBL environments was established. Research design could begin.

11.2.2. QUANTITATIVE STUDY

A quantitative study was designed and conducted. A commercially available instrument that has been used to measure self-directed learning readiness by most of the studies from the literature, and in nearly 100 previous PhD studies, Guglielmino's SDLRS, was utilized to conduct the study.

Participants came from groups entering the PBL study, exiting PBL study, entering non-PBL study, and exiting non-PBL study. The study period for all participants was the last two years of an engineering bachelor's education.

Mean-to-mean comparisons were made for the PBL group from pre- to post- and for the PBL vs. non-PBL groups. ANOVA t-tests were conducted using SPSS to acquire indications of statistical significance.

Four comparisons were made.

1. All PBL pre-post showed significant growth ($t = 2.5310$, $p<.05$).
2. PBL pre-post, same cohort, showed significant growth ($t =3.5101$, $p<.05$).
3. Non-PBL pre-post, showed no significant growth ($t =1.168$, not significant $p>.05$).
4. Post- PBL to post- non-PBL, showed significant positive performance difference ($t =3.2100$, $p<.05$).

The results of the quantitative study confirmed the results in the literature and the hypothesis that PBL students become more self-directed in their learning than students in non-PBL learning environments.

11.2.3. QUALITATIVE STUDY

With the knowledge from the quantitative study, a qualitative study was designed and conducted. Using a phenomenographic method, 27 PBL graduates were interviewed and analysis was conducted.

Upon completion of data collection and interview transcription, analysis of results began. The transcripts were read multiple times, each time resulting in an increasingly sophisticated perspective of the participants' experiences and views.

The result of the qualitative study was the emergence of two models for understanding how PBL students experience self-directed learning. The first model is the outcome space of the phenomenography. It is a set of the different "ways of experiencing." The different ways that PBL graduates view the meaning of self-directed learning. The second model is a composite representation of the elements of self-directed learning. This cyclic model includes all of the elements and an interpretation of how the elements are used to manage self-directed learning. The models were explained through theory and confirmed using the words of the interviewees through their quotes. In particular, the Illeris framework and the APA principles of learning were used to describe the participant models.

11.3. ANSWERS TO THE RESEARCH QUESTIONS

The main research question is "How do PBL students experience self-directed learning?". Under the overarching question are four sub-questions. They are the following:

1. What are the different elements of self-directed learning that students experience and to what level do all students experience the variety of elements?
2. How do PBL students develop compared to non-PBL students?
3. What are the different ways PBL students view self-directed learning?
4. How does PBL student development of SDL abilities align with theory?

In addition to the four sub-questions, whose answers are intended to provide knowledge that answers the main question, there is a question that proceeds the research question and an unexpected result that both contribute to body of knowledge.

Preliminary question

Before attempting to answer the research question about how PBL students experience self-directed learning, the question "Is there value in focusing on the development of self-directed learning in engineering education?" should be asked. In other words, it was necessary to establish value in the pursuit before beginning the research. Lifelong learning is both an ABET outcome and a Washington Accord graduate attribute. In Section 5.1, substantial evidence is provided in support of the need for independent management of one's own learning of technical knowledge for the entirety of the career. There is little evidence in the literature in that engineering educators provide explicit focus on (or skill development in) self-directed learning. Emerging from the literature review it was clear that self-directed learning should be highly valued by engineering educators.

Unexpected result - SDL comprehensive model

Prior to the study, it was anticipated that the results would provide some level of answer to the research question by addressing the sub-questions. There was, however, one unexpected result. That was the emergence of a single model of SDL process. In the qualitative study (Chapter 8), interview participants, while describing what SDL is and how they use it, indicated an extensive set of elements of self-directed learning. These elements were sought in an effort to answer sub-question 1. Additionally, though, their descriptions yielded the processes by which the elements were implemented (Chapter 10). These descriptions of actions and orders in which the actions were taken yielded a comprehensive model for implementation of SDL. The model, shown in figure 10.1, has the potential to be used in a variety of ways by curriculum developers and perhaps others. The emergence of this model is **finding #4** (figure 11.1) of this research study.

Sub-question 1: What are the different elements of self-directed learning that students experience and to what level do all students experience the variety of elements?

From the interview transcripts, using the students' words, 15 elements of SDL were identified. A value of the answers to this question is identifying which elements the students experience and then search for aspects that might be missing. There were some missing aspects identified in the qualitative analysis. They were self-monitoring of effort, management of and interaction with environmental factors, and social interactions during learning. This greater list of included and missing elements provides information for consideration as people contemplate how implementation of PBL impacts students' experiences in self-directed learning. **Finding #2** (figure 11.1) resulted from this portion of the study.

Sub-question 2: How do PBL students develop compared to non-PBL students?

The literature, as reviewed in Chapter 5, provides an indication that PBL educational experiences lead to higher levels of self-directed learning readiness. The quantitative results of this study, analyzed in Chapter 7, confirm higher levels of self-directed learning readiness. Four comparisons were made between pre-post PBL, pre-post non-PBL, and post-post PBL to non-PBL. In all of the comparisons, statistically significant results showed increased or better results for PBL groups and no gain or better performance for non-PBL learning groups. For these comparisons, the same established instrument was used by the researchers from the literature. Thus, **finding #1** of this study (figure 11.1) is further evidence that PBL learning experiences result in higher levels of self-directed learning ability.

Sub-question 3: What are the different ways PBL students view self-directed learning?

In the qualitative study (Chapter 9) emerged a variety of ways that students perceive self-directed learning. While the comprehensive model displays a potentially positive model of learning for adoption or adaptation, the ways of experiencing are not all positive. The list of ways that PBL students experience PBL is as follows: independence, responsibility/ownership, motivation/initiative, future value, managing the act of learning, and effectiveness of learning. For example, considering self-directed learning as wholly independent is a view that would prohibit learning from others. Whereas, managing one's own learning or being motivated to learn are both more sophisticated models that can lead to empowerment as learners. The value of **finding #3** (figure 11.1) is knowing that these different impressions exist and being able to explicitly design instructional activities that address the variety of expectations for the students in the environment.

Sub-question 4: How does PBL student development of SDL abilities align with theory?

The composite model of self-directed learning and the variety of ways PBL students experience are extensively described in terms of the theory (Chapter 10). In chapter 2, two theoretical frameworks were presented for ways to view learning environments. Illeris' model (Illeris, 2007) and the American Psychological Association learner-centered principles (APA, 1997) of learning were described and then used to analyze and describe the IRE model of PBL (Chapter 4). In Chapter 9, these same frameworks were used to describe and analyze the models resulting from qualitative analysis. Two items of interest arose. First, the elements of the models were well supported by theory. Second, there were "holes" in the models, places where theory could suggest valuable additions to the models. For example, the composite model of SDL is missing APA principles 6 (context of learning) and 10 (self-monitoring of effort) and is poorly represented on the interaction/incentive leg of the Illeris triangle. The value of this finding is such that curriculum developers and instructors who are considering implementing PBL, and are concerned with the development of self-directed learning, can contemplate how the strengths of the theory supported attributes of the PBL experience analyzed in this research might be relevant to the PBL experience being designed or implemented in their context. Further, they can consider how the "holes" in these models might be addressed in the implementation of their models.

11.4. FINAL REFLECTIONS

The goal of a PhD study is to add to the state of the art. The state of the art impact of this entire PhD work is highlighted by the four findings (figure 11.1).

The major intention of the research study was to establish characteristics of how PBL students, in the context of one program, develop as self-directed learners and then make those characteristics available for curricular decision makers to contemplate as they consider implementation of PBL or development of SDL abilities in their contexts. This has been done. These characteristics add to the state of the art and are evident in the answers to the research sub-questions, which comprise an answer to the main research question. In particular, the models developed in the qualitative study provide relevant knowledge for consideration.

I propose that the results of this work add to the growing body of knowledge that PBL education results in growth of self-directed learning abilities whereas, traditional engineering education does not. The literature predicted this result. The quantitative study in this PhD further strengthens the argument.

I offer that the contributing factor to the development of PBL students in self-directed learning abilities can be attributed to higher levels of motivation to learn that result directly from the structure of PBL. Self-determination theory attributes increased motivation to learn to higher levels of autonomy, connectedness, and competence. By its nature, PBL offers students many more opportunities to have control over their learning decisions (autonomy). Further, it offers many more opportunities to be connected to peers, faculty leaders, and learning through team-based projects (connectedness). Contrast this to university lecture halls where students arrive in class moments before it starts, sit in rows facing forward in large numbers, get lectured to throughout the class period, and leave in different directions upon the end of the class period. PBL principles simply provide for greater opportunities to increase student motivation to learn. Increased motivation to learn in a learner-controlled environment should lead to development in self-directed learning. The literature review for this thesis resulted in the opportunity to connect this theory to the increased development. Future work can be done to strengthen this hypothesis.

The first volume of this thesis brings to publication the description of the Iron Range Engineering model. My role in developing and implementing this model, including during the three years of this PhD study, is significant. In engineering terms, I am the “prime-mover” for the program. The program has many distinguishing characteristics (see volume 1, conclusion) that add substantially to the body of knowledge of PBL practice. I argue that this contribution has impacted the state of art of engineering education practice.

11.5. LESSONS LEARNED

The lessons learned in this PhD study are numerous, but mostly fall into the category of academic maturity that happens as a result of undertaking a PhD study. There were struggles in learning how to search literature, writing academically, composing research questions, thinking like a researcher, and gaining enough context to see the bigger picture of the work being undertaken. One of the biggest challenges was to remove myself from the center of my thinking and writing. The work would be rather boring and have little value to others if it was about me. Though this was obvious, it was hard not to slip into using my own experiences to justify conclusions.

Two transformational lessons resulted from writing this volume and completing the qualitative study. The first was the learning about the objectivism<—>constructionism and positivism<—>interpretivism tensions. I had unconsciously lived in an objectivist/positivist world without really considering constructionism/interpretivism. Through much reflection on teaching, learning, and life, I definitely had to align my beliefs with constructionism and interpretivism. This experience along with further reflection brought me to an understanding of multiple realities. An understanding that not each person experiences an event the same way, and that for each of them, their experience is their reality. This lesson has transformed the way I view the world around me, particularly the way I view the educational environments of which I am a part.

The second transformational lesson came from exposure to, and the learning of, self-determination theory. SDT has brought me to the understanding that the essential psychological needs of autonomy, competency, and connectedness impact levels of motivation. This perspective has given me a model to interpret many of my past experiences of success and failure as a teacher, student, and facilitator. It gives considerations for planning future learning activities and learning community environment attributes. Further, just as above, the lesson extends beyond the learning environments to everyday life, especially interpersonal interactions.

11.6. CRITIQUES OF WORK

The critiques of this work relate to both the structure of the research design and to my involvement in the research.

The quantitative study was limited to one survey instrument that returned a single score. Though this same instrument was used in this manner in the literature, the quantitative finding could be more valuable with additional confirming data using additional tools. Further, the instrument is designed to measure individual learning, leaving out the perspective of collaborative (social) learning.

The methodology and qualitative research design were focused on performing a phenomenography, which would result in only a “ways of experiencing” finding space. Despite this intent, another result emerged. The composite model addressed in finding #4 is not a phenomenographic result showing the variety of experiences of the individuals; rather, it is more a phenomenological result showing the composite experience.

My personal involvement with the study brings three issues to be addressed. They are the following:

1. I have a strongly embedded bias towards PBL and away from traditional engineering education. This bias is the result of 30 years of adult experience in engineering education. The bias is the reason I became involved in Iron Range Engineering and started this PhD. Though efforts have been made to be impartial, I’m certain my strong feelings have unconsciously impacted my interpretations of the research findings.

2. A further bias is towards the Iron Range Engineering model. I have been intimately involved in every aspect of the program from initial ideation through the present day. Making impartial judgments about the program or the students is as difficult as making impartial judgments about one’s own children. In another career, I coached varsity athletics. In order to make sound decisions, varsity coaches make judgments of ability about their players on a continuous basis. In this role, I coached two of my own children. I had to constantly calibrate myself and explicitly question my judgments. From my perspective, I successfully navigated those waters, though in hindsight know that there must have been places where I was blinded by my relationship to my children. The same can be said about this research. I constantly calibrated myself, explicitly questioning my judgments during this PhD study. However, just as in coaching, I’m certain there are places I have been blinded by my relationship to this program. I justify this fact with the belief that my closeness to the program brings many positive perspectives that others would be unable to present.

3. One additional criticism, to this research would be the relationship I have with the participants in the qualitative studies. This relationship was addressed as acceptable in the literature on phenomenography (Chapter 6) and was handled by me as addressed in the previous paragraph. It is a reality of this study, one that needs to be explicitly addressed as a critique.

11.7. FUTURE WORK

This study has opened the door to new avenues of future work to be considered for understanding the development of self-directed learning in engineering students. In a broad sense: 1) More quantitative measures should be evaluated and used to compare the development of PBL vs. traditional engineering students. 2) Quantitative tools could be developed to address the aspects of collaborative learning. 3) Qualitative studies should be undertaken to gain insight to the ways that traditional engineering students experience SDL and develop self-directed learning capabilities. 4) Research should be undertaken to identify the relationships between self-directed learning development and PBL implementation as a direct result of the social/connectedness attributes of PBL.

More specifically, future work that I intend to undertake includes the following:

1) Identify, evaluate, and implement additional quantitative measures for assessing SDL development of PBL students.

2) Elaborate the composite model of SDL that resulted from the participant responses to this study. The model can be improved by adding elements of learning from theory that were not addressed by the interview participants. The model can then be used in explicit SDL instruction. I intend to use this model to design either an action research or design-based research approach to be implemented at Iron Range Engineering.

3) I intend to begin a research study to explore the impacts of PBL social aspects on connectedness/motivation from SDT.

11.8. FINAL STATEMENT

Cited in volume 1 was the UNESCO Report "Engineering Education: Transformation and Innovation" authored by Beanland and Hadgraft (2013). This report speaks highly of PBL:

> *"A study by Mills and Treagust (2003) concluded 'that the use of project-based learning as a key component of engineering programs should be promulgated as widely as possible, because it is certainly clear that any improvement to the existing lecture-centric programs that dominate engineering would be welcomed by students, industry and accrediting authorities'."* (Beanland & Hadgraft, 2013)

> *"There is an excellent match between the education benefits provided by Project-based Learning and the Graduate Attributes required for*

> *Professional Engineers. It is not clear how these benefits could be more effectively delivered by any other educational processes or strategies…. It is now possible to identify that: The fourth step towards Transformation is the utilisation of Project-based Learning in each year of engineering education programs."* (Beanland & Hadgraft, 2013)

The Iron Range Engineering model of PBL was initiated because the developers shared this perspective (Ulseth & Johnson, 2010). The results of this PhD study concur. Specifically, the graduate outcome of being lifelong, self-directed learners is supported by PBL engineering education. Beyond this work, the PhD study of Bart Johnson supports PBL educations developing higher levels of professionalism graduate attributes.

As highlighted throughout volumes 1 and 2 of this thesis, there is a preponderance of data and findings on the efficacy of PBL engineering education. I believe it is time for engineering education, especially in the United States where resistance has been high, to embrace PBL models as the future mainstream educational model. This PhD study experience will serve as a springboard for me to be a facilitator in this movement.

VOLUME 2 LITERATURE LIST

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APPENDICES

Appendix A. Pilot Curriculum Description

Authors' description of IRE model at end of one year of model (Ulseth, Johnson & Bates, 2011).

"THE IRON RANGE ENGINEERING EDUCATION MODEL

The IRE model in the United States addresses the calls for change in engineering education. The primary emphasis is on the development of learning outcomes, contrasted with primary emphasis on coverage of topical material that characterizes many of the engineering programs throughout the world. The learning in the IRE model is 100% project based and is targeted at the development of a technically sound, highly professional graduate who possesses high levels of problem solving ability and has experience in engineering design. In an adaptation of the Aalborg Model of PBL (Figure 1), IRE students combine learning of technical information and professional development with the execution of engineering design projects. A guiding principle for the IRE model is that, throughout the projects, students own the responsibility for their learning through the projects while obtaining the technical and professional knowledge and competencies which have been defined for the program.

Project Cycle

The core of the IRE model is the learning that takes place around engineering design projects. At the beginning or "proposal stage" of each project cycle, students, in collaboration with faculty and clients, develop two plans: a design "work plan" which details the entire execution of the deliverable to the client; and a "learning plan" which addresses professional learning objectives, technical learning objectives, and the learning modes that will be employed to meet the objectives (self-directed learning, peer-directed learning, faculty-directed learning, and external expert-directed learning as well as methods for formative assessment and reflection). Students execute one to two project cycles per semester.

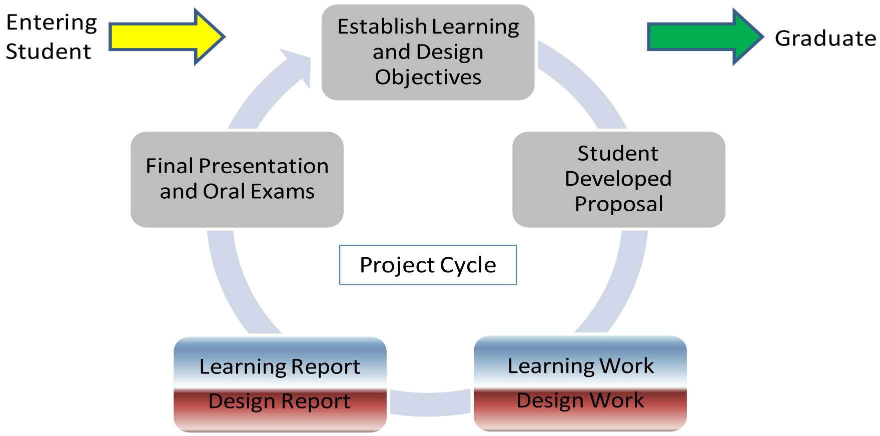


Figure 1. Iron Range Engineering Program Model of PBL: Adapted from the Aalborg Model of PBL (Kolmos, 2004).

Each cycle concludes with the presentation of two reports: a design report for the deliverable and a learning report that reflects the learning process and provides evidence of outcome attainment. In addition to written reports, a student presentation is made to faculty and external clients. The final presentation includes an extensive oral exam in which students show their understanding of technical engineering knowledge and the competencies acquired. At the conclusion of each project cycle, students have a new view of their levels of knowledge and competencies.

Technical Competencies

For each technical competency, assessment is done on a continuum, from novice to expert, using Bloom's modified taxonomy (Krathwohl, 2002). During the student's first semester, her individual starting point is established through working with faculty. In this way, the IRE model recognizes each student's different starting points and empowers all students to build on their strengths and overcome their weaknesses as they navigate their education. Each semester students achieve eight technical competencies. For core competencies (eight mechanical and eight electrical), there is a fixed syllabus. For advanced competencies, students work with faculty to develop a personalized syllabus. In all cases, a technical competency consists of the development of knowledge through deep learning activities (Litzinger, 2011). Upon starting a project and meeting with industry clients, students identify which core and elective competencies best meet their individual and project needs. Some technical competencies are learned early in the semester as necessary background knowledge. Others naturally develop during project execution and are learned later in the semester. To graduate, students must attain "work ready" competency in core and advanced competencies.

Throughout the learning process, students have multiple interactions with faculty, learn through self-study and in peer groups, and tie their learning to their projects. Students regulate their learning through organization of new knowledge, evaluation of quality of learning, and making in-progress changes to learning based on those evaluations. Each week, students meet with faculty in a “Learning Review” to discuss progress, impediments and plans for learning in the upcoming week. Students take oral and written exams, and provide evidence of deep learning for each competency. Students complete course and graduation requirements by exceeding or meeting levels of competencies based on clearly articulated outcomes.

Professional Competencies

At the beginning of the IRE experience, students also identify all of the professional competencies or attributes that are expected of them by graduation. Working with faculty, they gauge their baseline in each attribute. Each semester, faculty provide learning activities in leadership, learning about learning, team work, communication, personal responsibility, professional responsibility and the entire spectrum of executing the design process. Through reflection, personnel evaluation by project mentors, client feedback, peer feedback, and faculty evaluation, students track their advancement towards their graduation goals. At the end of each semester, students write improvement plans for the next semester including specific activities aimed at enhancing their performance.

Through PBL, industry interactions, and significant metacognitive activity, students develop advanced problem solving skills, deep technical knowledge in the fundamentals of engineering, advanced knowledge in selected disciplines, and a well developed set of professional skills such as writing, speaking, project management, leadership, conflict management, and ethical decision making. The expectation is that these experiences will lead IRE graduates to meet the ABET a-k student outcomes (ABET, 2009) at levels much higher than in traditional US programs.

Appendix B. IRE Graduate Student Outcomes

Technical Outcomes	**Design Outcomes**	**Professional Outcomes**
Tech 1. *An ability to apply knowledge of mathematics, science, and engineering* • Describe concepts in an oral exam • Solve closed-ended problems • Use knowledge in a deep learning activity Tech 2. *An ability to design and conduct experiments, as well as to analyze and interpret data* • Design an experiment to answer a question related to technical work • Acquire experimental data and compare results to appropriate variables • Explain observed differences between model and experiment and offer explanations Tech 3. *An ability to identify, formulate, and solve engineering problems* • Choose and apply appropriate engineering principles needed to solve an open-ended problem • Determine the reasonableness of a solution to an open-ended problem • Evaluate the completed solution	Design 1. *An ability to design a system, component, or process to meet desired needs within realistic constraints* • Accurately report a scoping process for a project in writing and verbally • Conduct the design process iteratively to develop a solution meeting the requirement • Critically judge design solution effectiveness based on project requirements Design 2. *An ability to function on multidisciplinary teams* • Establish a team contract setting team expectations and assign appropriate roles • Analyze effectiveness of the group during the project • Evaluate quality of teamwork achieved and its impact upon satisfying project requirements • Individually contribute appropriately to completion of team project. Design 3. *An ability to lead, manage people and projects* • Create a team time budget based on a list of tasks within a project • Implement a team course of action to finish all required tasks by a deadline. • Evaluate effectiveness of one's ability to lead, manage people, and manage projects; develop a plan for future improvement	Prof 1. *An understanding of professional and ethical responsibility* • Write professional development improvement plans, semester by semester • Actively participate in multiple outreach activities per semester • Take part in and document regular design project ethical implication conversations • Meet the Professional Expectations of an IRE student Prof 2. *An ability to communicate effectively* • Communicates project details verbally to various audiences • Communicate technical information to student peers • Analyze individual communication effectiveness and develop an improvement plan • Complete "Jobs Package" • Develop Personal Marketing Plan • Evaluate others' writing and presentations and provide feedback Prof 3. *An ability to work successfully in a diverse*

process to determine effectiveness Tech 4. *A recognition of the need for, and an ability to engage in life-long learning* • In learning journal, demonstrates effective learning principles • Develop and communicate personal learning model in a learning journal • Apply Metacognition techniques to improve individual learning in a metacognition memo Tech 5. *An ability to engage in entrepreneurial activities* • Recognizes the financial impacts of the proposed design. • Choose and apply business concepts to products and processes.	Design 4. *An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice* • Document a wide range of acquired technical skills and techniques through the development of a "best works" portfolio of their engineering practice • Document acquisition of and growth in professional skills and techniques through periodic personal performance evaluations • Solve advanced engineering calculations and perform design analysis using modern tools Design 5. *The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context* • Identify and apply contextual knowledge that influences design solutions. Examples include, but are not limited to these: health, safety, environment, global, societal, ethical, moral, legal, financial, human, and lifecycle.	*environment* • Write PDP goals that show that interacting with others in a professional and respectful manner in all situations is a critical tool for success. • Maintain a daily work environment free from behaviors and speech that cannot be tolerated in an engineering environment. • Demonstrate an understanding of unconscious bias and its implications. Prof 4. *A knowledge of contemporary issue* • Demonstrate awareness of contemporary issues

Appendix C. IRE Project Solicitation

Educational Scope:

IRE student projects are meant to serve two purposes: 1) provide engineering students with an experience that enables them to develop project management skill, technical expertise, design experience, and professional competency, 2) contribute, in a meaningful way, to the client by meeting the client's defined need.

Process:

At the beginning of the semester students and their IRE faculty mentor will meet with the client in a scoping meeting to identify deliverables, constraints, timelines, and resources. At this time, the project team and the client will agree on periodicity and types of communication to take place during the project. After the scoping meeting, students perform background research, complete a scoping document, develop options, design experiments and models to test the options, select an option, and execute the design to meet their client's deliverable needs. Each student spends 15-20 hours per week working on this process. They spend an additional 25-30 hours per week completing their technical and professional learning for the semester. The best technical learning takes place when it is directly related to the team's project. At the end of the semester the students will have created a significant (often 100+ page) technical document detailing their design process, they will present their technical document, as well as the design deliverables, to the client in a formal presentation.

1. Project description (1 paragraph summarizing project):
2. List of specific desired deliverables at end of project:
   -
   -

3. Anticipated length of project (one or two semesters): _________

4. Suggested number of students working on project: __________

5. Areas of engineering technical knowledge students will need to acquire through execution of the project (e.g. thermodynamics, power distribution, foundation design, etc.)
   -
   -

6. Contact information for primary contact at your company:

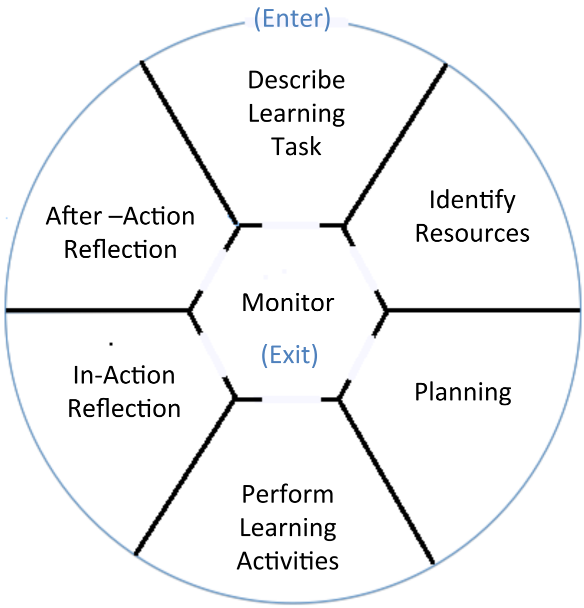
   Name: ________________________________

Email: ____
Phone: _______________________________________
Cell: ____

Attributes of successful IRE projects:

- Meaningful and realistic projects
- Clearly defined expectations
- Responsive communication in both directions
- Multiple opportunities for students to spend time on-site learning and interacting with engineers and technicians

Appendix D. IRE Metacognitive Process



There are two steps to the metacognitive processes used at Iron Range Engineering.

1. Learning Journal
2. Metacognitive Memo

Learning Journal Requirements –

[Due to the importance of these metacognitive activities to the practicing engineer, and in the development of the future engineer, we request you use a learning journal for all of your learning activities.]

1. Prior to learning, write your pre-learning paragraph. Include a sentence or two describing the learning task and a sentence or two describing the resources you will use.

2. Plan and write down a list of the steps you will follow to achieve the learning task. Make a brief indication of the intensity and speed you intend to bring to this task.

3. Do the learning. This does not have to be recorded in your learning journal. It can be taking notes while reading or in an LC, or solving problems on a white board, or working on a DLA. It is the performing of the activities you do to learn.

4. Perform an in-action reflection in which you write a few sentences summarizing what has been accomplished, make judgments on the speed, estimate % done, and predict the likelihood for success.

5. Write after-action summary. Describe current status of learning task accomplishment, future value of learning, future plans, etc.

* As you move from step to step in your journaling, practice using the monitor questions. Does my plan meet my need? Are my resources adequate? Am I on pace to succeed? Which "room" should I enter next? Etc.

Metacognitive Memo Requirements –

[One metacognitive memo is due at the end of each IRE block. It will address all of the learning you completed during that 8 week period and will be a factor in the grade for each technical competency on which you worked.]

Write in memo form:

Date: (date of writing of memo)

From: (you)

To: (your technical competency instructors)

Subject: Metacognitive Memo (block __, of _______ semester, _____(year))

1. Paragraph 1 – Block Overview (Briefly describe the courses taken including major principles learned and DLA's completed).

2. Paragraph 2 – Learning Journal Use (comment on the extent to which you used your learning journal to perform the metacognitive tasks: identifying learning tasks, identifying resources, planning learning, reflecting in-action, and reflecting after action)

3. Paragraph 3 – Learning Journal Quality (use the 1-5 scale of 1-deficient, 2-weak, 3-acceptable, 4-desired, 5-exemplary) to rate your use of metacognition. Provide 2-3 sentences of evidence defending your rating.

4. Set goals with action plans for improved use of metacognitive strategies in your next block.

Appendix E. Co-Author Statement

Co-author statement in connection with submission of PhD thesis

With reference to Ministerial Order no. 1039 of August 27 2013 regarding the PhD Degree § 12, article 4, statements from each author about the PhD student's part in the shared work must be included in case the thesis is based on already published or submitted papers.

Paper title: Self-Directed Learning in PBL

Publication outlet: PhD Thesis

List of authors: Ronald Ulseth, Bart Johnson

PhD student: Ron Ulseth

Scientific contribution of the PhD student (all participating PhD students) to the paper:

- **PhD student:** The PhD student and the co-author co-wrote Volume 1 of this thesis. The PhD student independently authored his own Volume 2. Volume 1 is the theoretical & historical background of work that led to our own individual research work. The co-authorship will be acknowledged at the beginning of each shared chapter in Volume 1 and in the table of contents. Following is a breakdown of section by section lead authorship:

  -In chapter 1, there are 6 sections. The PhD student was the lead writer on sections 1.4, 1.5, and 1.6.
  -In chapter 2, there are 5 sections. The PhD student was the lead writer on 2.2 and 2.3 and co-writer of 2.5.
  -In chapter 3, there are 7 sections. The PhD student was the lead writer on 3.1-4 and 3.7.
  -In chapter 4, there are 9 sections. The PhD student was the lead writer on 4.1-3.

  Lead writer corresponds to having done the majority of the background research, planning on a section, and edit work. In all cases, each person provided section development contributions and edits on the work of the other author.

  Volume 2 is the research work of this thesis and was completed independently, in its entirety, by PhD student.

- **Co-author (also a PhD student):** The co-author equally contributed to the theoretical & historical background work of volume 1. Volume 1 has four chapters.

  The co-author was the lead writer on sections 1.1, 1.2, 1.3
  The co-author was lead writer on the 2.1 and 2.4
  The co-author was the lead writer on 3.5 and 3.6.
  The co-author was the lead writer on 4.4-9

  Upon completion of volume 1, the co-author completed, independently, the research and writing of his volume 2.

A copy of this statement will be included in the appendix of the thesis.

Signature, PhD student

Signature, Co-author

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