2022

Project-Based Learning in Non-Traditional Settings in Engineering Education

Mary Foss

PROJECT-BASED LEARNING IN NON-TRADITIONAL SETTINGS IN ENGINEERING EDUCATION

BY

MARY FOSS

A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy

Major in Mechanical Engineering

South Dakota State University

2022

DISSERTATION ACCEPTANCE PAGE

Mary Foss

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Yucheng Liu
Advisor Date

Zhong Hu
Director Date

Nicole Lounsbery, PhD
Director, Graduate School Date

This dissertation is dedicated to husband and my children. For all the nights my husband stayed up late with me as I wrote papers and solved math problems and for every moment he stayed by my side with words of encouragement, support and dedication. For my children for falling asleep on my lap as I watched video lectures and for helping me keep perspective when all seems lost. I couldn't have done this without you.

ACKNOWLEDGEMENTS

I'd like to acknowledge my advisor Dr. Liu. In 2018 he agreed to accept me as an advisee. From the beginning, he understood the demands I had outside of this degree program and has been steadfast, reliable and dependable. He has taught me so much through our distance relationship in his professionalism and responsiveness and commitment to his students and the field of education. Though we have not met in person and only spoken a few times, I am amazed at what we have accomplished.

I'd like to acknowledge my graduate committee Dr. Michna, Dr. Walker, and Dr. Nguyen for your willingness to allow me to continue to progress with Dr. Liu and helping me become integrated within SDSU as well as Dr. Hu for responding to my many questions. Thank you for working with your schedule to meet with me and serving on my committee and for your support.

I would also like to acknowledge my dean from Weber State University, Dr. David Ferro that has supported me through this process with understanding and guidance and friendship and invested in me to achieve this goal. Also, all my colleagues at Weber State University that check-in and remind me why I'm doing this and my own students that I hope will see the benefit of this endeavor.

TABLE OF CONTENTS

ABSTRACT

PROJECT-BASED LEARNING IN NON-TRADITIONAL SETTINGS IN ENGINEERING EDUCATION

MARY FOSS

2022

The purpose of this study is to examine the effectiveness of utilizing the principles of Project-based learning (PJBL) in nontraditional settings in engineering education. There is ample literature related to the usage of PJBL techniques in engineering education but there are also challenges with incorporating PJBL within the curriculum. It is the aim of this dissertation to build upon this understanding of the advantages and limitations of PJBL in engineering education and identify areas within the existing body of knowledge in which more research is needed. This dissertation divides this topic into 4 sub-topics. The first sub-topic explores how PJBL can be utilized in non-classroom settings and is detailed in Chapters 2-4. In Chapter 2, the application of PJBL in engineering outreach is explored. It is found that through PJBL learning challenges, high-school age girls can be exposed to engineering disciplines in a positive and supportive environment where girls and women are promoted. This chapter details the format of the event 'Parent Daughter Engineering Night' as well as lessons learned and practical methods to create an event based upon PJBL methodology that reduces stereotype threat and increases belonging. Chapter 3 describes operation and management of an on-campus center designed with PJBL methodology. This chapter describes the benefits to the University and the community through detailed examples of projects as well as provides lessons learned in project selection and student intern

management. Chapter 4 identifies 10 maxims of promoting creativity in engineering education that have been identified by Kazerounian and Foley. This chapter addresses each of these maxims by providing an example in the ways in which PJBL can be used as an explicit means of developing creativity in engineering students. The next subtopic is how PJBL can be utilized in non-traditional classroom settings. Chapter 5 describes a PJBL challenge that can be used in a virtual learning environment that functions to bridge course content in one project by including elements of manufacturing processes, material science, and applied statistics. This chapter presents the PJBL challenge as a case-study and highlights key learning outcomes that can be achieved. The next subtopic is intended to examine how PJBL is supported by theories of learning. Chapter 6 describes existing theories of learning and provides 6 different mathematical models of learning that are then evaluated using tools of applied mathematics. In this chapter, strengths and weaknesses of each model are considered as well as the future need to evaluate a learning model with empirical data. Lastly, the final sub-topic highlights the ability of PJBL to function as a tool to promote social change. Chapter 7 describes the United Nations Sustainable Development Goals (SDGs) and the responsibility of educators and future engineers to address these goals. In this chapter, examples are provided of explicit ways in which PJBL can serve the dual purpose of promoting engineering education through the completion of projects that are intended to support or promote the SDGs.

Chapter 1

Introduction

1.1 Introduction to Study

The modern engineering profession is dynamic, filled with uncertainty, and requires a technical background as well as interpersonal skills and most notably a mindset that is flexible, creative, and adaptable. The demands placed on modern engineers are to navigate and act upon competing priorities set by clients, regulating bodies, environmental groups, and the public at large to solve the problems of modern society. For engineering students to be prepared for the challenges they will face in their careers, they need to gain experience working in a dynamic environment to solve projects and problems that diverge from the theoretical realm and enter a practical landscape similar to what they will encounter in industry. One such way to do so is with project-based learning (PJBL).

The PJBL process is student-driven and facilitated by the instructor. Learners are encouraged to pursue knowledge by asking questions. PJBL is regarded as a key strategy for creating independent thinkers and much research has been done on incorporating PJBL into K12 education as well as higher education. Much of this research is primarily qualitative though there exists a substantial body of knowledge of quantitative research as well.

1.2 Objective of Work

There is ample research on PJBL in K12 education and in traditional engineering education environments. Research suggests that PJBL is a promising solution to achieve many of the 21st century objectives of education.

However, research identifies practical challenges to implementing PJBL on a larger scale within the course curriculum. At the individual level, there is a need for training for teachers on how to facilitate a PJBL challenge and also understand elements of effective PJBL design. There is also a challenge with developing effective assessment methods. Since PJBL involves the completion of projects, there is an inherent subjective nature of assessing students' learning that is accomplished. There are other challenges related to the institution including infrastructure, equipment and tooling and the need for more time, effort, and support to design effective PJBL curriculum that captures key learning outcomes in a particular course.

Additionally, the fundamental learning process itself is understood through a philosophical basis of learning theories and is very individual in nature. This makes the prospect of quantifying the ‘right’ way to teach impossible and thereby proving PJBL is the ‘right’ way to achieve learning outcomes for students.

It is the aim of this dissertation to build upon this understanding of the advantages and limitations of PJBL in engineering education and identify areas within the existing body of knowledge in which more research is needed. The following represent the objectives of this work and the methodology that is used to meet the objective. The below chapter summaries are intended to provide the reader with an overview of this dissertation. Each chapter is written with a stand-alone introduction and background section to familiarize the reader with the existing literature about the topic and relevant background information.

Chapter 2 was published as "PJBL as Tool for Engagement in Engineering Outreach: Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines". This chapter was coauthored by Foss and Dr. Liu and was published and presented at the summer 2022 American Society of Engineering Education held in Minneapolis, Minnesota under the category "Women in Engineering." It is the goal of this chapter to evaluate the use of integrating PJBL challenges into engineering outreach efforts to promote women in engineering.

Chapter 3 was published as "PJBL Center to supplement education with real-world experience: Creating Solutions through Project-Based and Experiential Learning: A Case Study of the Concept Center." This chapter was coauthored by Foss and Liu and was published in the *International Journal of Engineering Education*, Volume 37, No. 6 in December of 2021. It is the goal of this chapter to capture the diversity of projects that can be completed at a center designed upon the principles of PJBL and the resulting student learning outcomes.

Chapter 4 was published as "PJBL Supported through Application in non-traditional classroom settings: PJBL as a tool to Develop Creativity: Developing Creativity Through Project-Based Learning." This chapter was authored by Foss and Liu and was presented and published at the Wasatch Aerospace and Systems Engineering Conference hosted by the American Institute of Aeronautics and Astronautics (AIAA) in April of 2021. This chapter was awarded second place in the category 'Championing

Change' by the conference judges. It is the goal of this chapter to tie the PJBL to each of the 10 maxims of creativity in engineering education.

Chapter 5 was published as "PJBL as a tool to bridge course learning outcomes in virtual settings: Project-Based Learning in a Virtual Setting: A Case Study on Materials and Manufacturing Process and Applied Statistics." This chapter was co-authored by Foss, Liu and Yarahmadian and was published in the *International Journal of Engineering Education* Vol. 38, No. 5(A) in September of 2022. It is the goal of this chapter to examine a specific PJBL challenge that can be applied to a virtual or online course.

Chapter 6 is published as "An Evaluation of Mathematical Models and Stability Analysis of Learning Based on Reaction Kinetics". This chapter was co-authored by Foss, Liu, and Yarahmadian and has been accepted for publication and presentation at the International Science, Engineering and Technology Conference (IConEST) in Austin, Texas in October of 2022. The goal of this chapter is to examine existing theories of learning and propose a mathematical model of learning based upon reaction kinetics. It is not the goal of this chapter to conclude the model is correct or complete but to rather examine the usage and application of tools of Applied Mathematics in evaluating the suitability of a learning model that could later be examined using quantitative methods.

Chapter 7 is published as "PJBL as Means to Promote Social Change: Promoting United Nations Sustainable Development Goals Through Project-Based Learning". This chapter was co-authored by Foss and Liu and has been accepted for publication and presented at the United Nations 1st Annual Academic Conference of the Sustainable Development Goals in October of 2022. This chapter intends to highlight a PJBL center as a solution to achieve many if not all of the United Nations Sustainable Development Goals.

Chapter 2

PJBL as Tool for Engagement in Engineering Outreach

Abstract

Parent Daughter Engineering Night is an outreach event targeting 7^{th}-12^{th} grade girls hosted by Weber State University. This event joins a parent with his or her daughter for an evening of engineering challenges designed with problem-based learning (PJBL) methodology. This chapter describes the need to address some of the psychological factors of under-represented minorities (URM) within engineering. By creating an environment where belonging is promoted and stereotyping is decreased, the Parent Daughter Engineering night achieves an atmosphere that is inclusive of women and girls. This event is designed to demonstrate the role and place of women in the engineering disciplines through guest speakers and facilitators. This chapter describes the basic structure of the event and schedule and details the engineering challenges that have been used for the past five years of hosting the event. This chapter describes key lessons learned in the organization and facilitation of the event as well as opportunities for virtual events to be held to target communities that are not located near institutions of higher learning. Finally, this chapter concludes that the Parent Daughter Engineering night event is a positive way to promote the inclusion of girls into engineering fields and connect with the K12 community.

2.1 Introduction

Many agree that a parent is a child's first teacher. The inspiration for the Parent Daughter Engineering Night Event hosted by Weber State University is based upon this premise using principles of problem-based learning (PJBL). This event has been hosted for a period of eleven years with the past 5 years including Foss being an event planner and facilitator.

In this setting created by the event, parents see their daughter in a positive atmosphere that not only supports but demonstrates the place of women in engineering. Additionally, the daughter, with a target age group of grades 7 through 12, can find herself in a group of her peers engaging in hands-on engineering activities and hearing the stories of women in engineering as students or in their careers. The result is both parties can share in an experience that uplifts and supports women in engineering and visualize a potential future for the daughter in engineering.

2.2 Background

2.2.1 Women in Engineering by the Numbers

The role that women have played in the field of engineering is historically complex but is also changing. In 2007 2.6% of freshmen women had intentions to major in Engineering compared to 13.7% for men. By 2014, the percentage of freshmen women intentions increased to 5.8% while for freshmen men the intentions increased to 19.1% [1]. These increases in both genders show a marked improvement that could be attributed to many factors, including focus on Science, technology, engineering and math (STEM) in primary and secondary education. These increases are also reflected in the number of science and engineering bachelor's degrees awarded to women in engineering and computer science with increases from 230,797 in 2004 to 309,698 in 2013, representing an increase in approximately 34% [2]. The clear evidence of women going into these disciplines can be attributed to a number of efforts in outreach to women and other under-represented minorities (URMs). However, despite these advances, there remain interesting trends in retention of URM students in STEM fields. Proportionally, 32% of females left STEM fields by switching to a non-STEM major compared to 26% for males [3]. There also exist significant gender imbalances within these fields in both the educational setting as well as industry. For example, the percentage of women working as engineers is 8.7% for mechanical and 11.8% for electrical and electronics [4]. The stark gender imbalances within engineering disciplines creates a catch-22 situation. More women would be represented in the educational setting and in industry if a critical mass of women could be achieved, eliminating or reducing challenges related to stereotypes and stereotype threat and belonging.

Stereotyping exists as a perception that a group of people have less academic ability. This ultimately has been attributed to a factor that's leads to dis-identification and dropout. Stereotype Threat has been identified in a number of studies. Women were shown to perform more poorly on math GRE items when taking the test with two men compared with two women [5]. Schmader and Johns explained the effect of gender imbalance on math task performance by reduced working memory while other studies have also found similar results on academic performance reductions due to gender imbalance [6, 11-14].

Belonging is another predictor of success and retention within engineering degree programs. A sense of belonging refers to a subjective measure of a student's feelings of being accepted, valued, included, and encouraged by both peers and teachers in the academic setting as well as a feeling of being an important part of the class [7]. Research has found that students that remain in STEM majors report a greater sense of belonging than their peers that leave STEM. Students from underrepresented groups are less likely to feel that they belong. Part of this reason is the numerical underrepresentation of the female gender in the educational and industrial setting [7-10].

2.2.2 Project-Based Learning

PJBL was developed in 1965 by 5 faculty of Health Sciences doctors led by founding Dean John Evans of McMaster University [15]. It is a learning approach in which students solve problems in small groups under the supervision of a tutor [15]. The PJBL process is driven by the student, facilitated by the tutor, and is based on an educational approach where the learning is driven by problems or can be thought of as “learning through application”. In this approach, learners (students) are encouraged to pursue knowledge by asking questions. PJBL has been regarded as a key strategy for creating independent thinkers and learners in the medical education community [15,16].

Following the implementation of PJBL in the education of medicine, it has since been expanded to other fields and is considered a solution to some of the issues facing today’s education [16]. For example, faculty at Weber State University established a PJBL center to achieve a double mission of being an active community member and providing opportunities for engineering students to gain needed skills in problem solving and project management [17-22]. It has been found that the PJBL learning approaches greatly facilitated the training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning [23-28]. Liu and coworkers successfully integrated the PJBL mode in his senior mechanical engineering classes by introducing more than 20 projects from industry sponsors, university research centers, and a state agency [23-26]. It was found from Liu’s practice that the implementation of PJBL in course curricula struck the balance between achieving desired student learning outcomes and creating opportunities for enriching the student's educational experience [27-34].

2.3 Parent Daughter Engineering Night

2.3.1 Background of Event and Funding

The original format of the Parent Daughter event took place over a weekend during the day. This was later reconfigured to be modeled like a 'night-out' that was held with two possible dates to attend over in two separate locations to accommodate families from different counties in the northern Utah area.

The event has been made possible by a grant, sponsorship from the Weber State University student chapter of Society of Women Engineers, a small registration fee for the parent daughter teams of $10, and volunteers. The event has a budgeted cost of $5,300 which includes the advertising and promotional materials, facility costs, challenge materials, t-shirts, dinner for all participants, and facilitators. The facilitators do all the planning and provide all of the supplies including prizes, t-shirts, and engineering challenge materials. The Center for Technology Outreach office provides the marketing materials and also organizes many of the logistical details of the event including securing the location, arranging a website for sign-up, and recruiting volunteers to help support the event. The event typically engages approximately 80 parent-daughter teams each year from the Northern Utah area.

2.3.2 Example Format and Schedule

The event changes each year but has been successful with the following format and schedule and is tied to together with a theme. Parent-Daughter teams arrive early to check-in and then are seated in a large banquet hall at tables with other teams. The event includes two engineering challenges that are intended to represent differing facets of the engineering disciplines. For example, one engineering challenge could target principles of mechanical engineering while the other could target electrical engineering. The engineering challenges begin with an overview of the challenge from the facilitator and the related background information that applies to the challenge. The facilitator will then direct the teams to begin the challenge with the materials provided. A typical schedule is shown below:

6:00 Event Start and Icebreaker

6:15 First Challenge

7:00 Dinner and Guest Speaker

7:30 Second Challenge

8:30 Event Close

2.3.3 Example Engineering Challenges

A summary of the theme and description of the engineering challenges is a useful way of demonstrating the objectives of the event to introduce parents and daughters to concepts in engineering through PJBL.

The event in 2017 had a Steampunk theme. The first challenge that was presented was for the teams to design and build a hydraulic hand that could pick up a wad of chapter. The teams were provided simple materials including plastic tubing, tape, 2 syringes, craft sticks, rubber bands, and decorative materials such as stickers. Near the close of the challenge, each team demonstrated their hydraulic hand completing the task. The second challenge was focused on the critical role of test engineers. The teams followed detailed instructions to build a circuit that could be used as a heart rate sensor.

Like the first hydraulic hand challenge, teams were limited in time and given all of the materials needed to complete the challenge. Through the duration of both of the events, the facilitators and volunteers were present to help the teams with the challenge.

The event in 2018 had an Energy Theme. The first challenge was to design and build a tower that could withstand an earthquake. The focus of this challenge was to introduce the engineering design process and direct the teams to follow each of the steps with the opportunity to test and redesign built into the challenge. Teams were given non-hardening modeling clay, coffee stirrers, and decorative supplies to build the tallest tower possible that could withstand an earthquake that was simulated at a testing station. The earthquake testing zone was built with a platform mounted above a reciprocating saw that simulated a ten second earthquake. The teams were encouraged to test their design frequently and then modify their design to improve the structure as well as over-all height. The second engineering challenge was to design a jewelry box with a light emitting diode (LED) and light sensor with battery to illuminate a light when the lid was open as shown in Figure 2.1. The teams were given all of the materials to make the box including ways to customize it and decorate it.

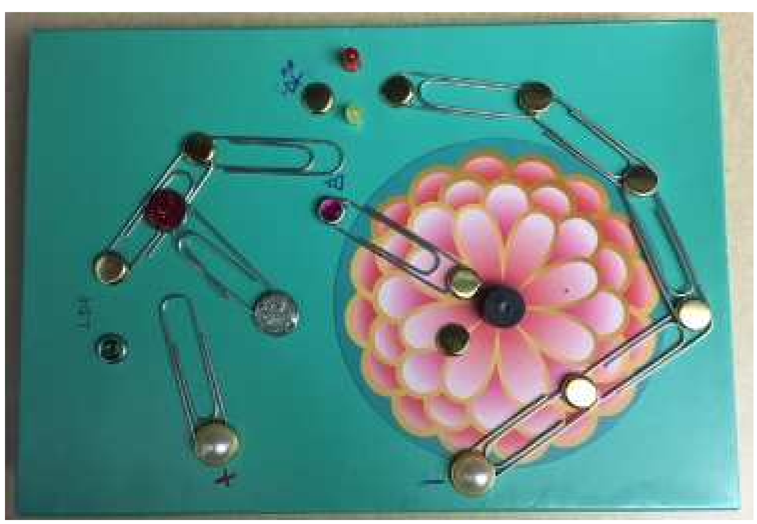

Figure 2.1. Magic Box Circuit Design Challenge.

A London theme was used for the event in 2019. The first challenge was to design and build a composite bridge. The goal of this challenge was to introduce teams to the growing field of composite materials. Teams were provided with fiberglass, carbon fiber, foam core, craft sticks, glue sticks, and school-glue. While, notably, using thermoplastics as the resin for the composite presented a number of challenges (primarily, the hardening time extended beyond the end of the event), it did demonstrate the concept of composites without the complication of using a thermosetting material and resulting safety concerns and necessary supplies such as safety glasses, gloves, and ventilation. The second challenge was to design and build a Zip-line Racer using provided materials. Teams were instructed to design, build and test a zip-line assembly.

In 2020, the format of the event changed drastically due to the ongoing Covid-19 pandemic. At that time, there was no allowance for any in-person events, so the event took on a virtual format. The theme for this event was outer space. Prior to the event, parents were instructed on picking up all the materials needed for the event and given a video conference link to join. The first challenge was to design, build and test an Effervescent Rocket. Teams were provided with all the materials including film canisters, cardstock, decorative materials, an alien passenger, and enough effervescent tablets for four test launches. Teams were also given a few optional problems to solve related to projectile motion. The second challenge was to design, build and test a Lunar Lander vehicle that could safely withstand a fall from a height without ejecting the vehicle passengers from the vehicle.

The theme for the event in 2021 was a carnival theme. The first challenge for the event was to design, build and test a crane claw machine to pick up a stuffed animal using a hydraulic system. The second challenge was to formulate and test a super ball and collect data related to the height of the bounce of the ball using isopropyl alcohol and sodium silicate. For both challenges, teams were provided with relevant background information regarding the scientific principles of the challenge as well as all materials.

2.4 Lessons Learned

2.4.1 For girls, by women

For the past 5 years, this event has been organized and facilitated by women faculty members and the Center for Technology Outreach housed in the college of Engineering, Applied Science and Technology (EAST). This partnership between faculty members and the outreach office is not intended to be a recruiting effort for the University specifically, but rather to promote the belonging of women within the engineering disciplines. While there is no requirement that facilitators are women, it does demonstrate in a powerfully non-verbal way the ability of women to belong in these disciplines to not only the girl, but also her parent or caregiver [28, 29]. Faculty members involved have represented Electrical Engineering, Mechanical Engineering, and Manufacturing Systems Engineering.

2.4.2 Guest Speakers

Guest speakers should also represent the focus of women in engineering. It is preferable if they are close to the next stage from the students, meaning they are college students themselves or recent graduates. Guest speakers that are closer in age to the attendees are easier to relate and connect to [28, 29]. Events in the past have had guest speakers including the presidents of the Society of Women Engineers chapter and recent graduates in the early stages of their careers. Typically, the event is scheduled so that the parent and daughter teams are served dinner while the guest speaker is presenting and there is a scheduled time for questions and answers at the end of the presentation. The most impactful guest speakers are share personal stories of their experience in engineering in a relatable way. For example, one guest speaker, Miss Cope, described her interest in engineering early on from building a Barbie house with her dad and her ambition as a child to be a "ballerina-Porsche mechanic". These stories help to create a playful atmosphere for all attendees and also make the guest speakers more relatable as they describe the experience of being an engineering student and/or as a woman engineer.

This portion of the event is often the most surprising because there tends to be a lot of engagement between the guest speaker and the attendees. Girls and parents alike have a lot of questions about the rigor of the degree and the career culture afterwards. These questions are often tricky in this environment, but the best answer is the honest answer. For example, in the event in 2019, the guest speaker was in her last semester as a dual major in Computer Science and Web and User Development and also was the President of the SWE chapter at Weber State University. A girl in the audience asked her if she had ever failed a class and she answered with a story of a class that she did fail. She described the emotions she felt in this experience and her determination to try again. These kinds of questions and stories can be so impactful to all students that question whether they belong in the engineering discipline when they experience failure in their degree [29].

Another sensitive question arose in the event in 2020 to the guest speaker about her experience with discrimination as a recent graduate. Her answer was sincere and honest as she described a negative experience with a colleague but also affirmed that she felt supported and valued by other colleagues on her team. While it might be tempting to paint the experience of women or any URM as free from discrimination, this can function to alienate those that are experiencing it. The reality is, the story of women in engineering is complex and is understandably not without growing pains. It is better to address the reality that it is likely women will face challenges related to their gender over the course of their careers but there are strategies to handle these challenges as well as support networks such as SWE. By using lived experiences to answer questions from parents and daughters, attendees can be prepared for some of the challenges they are likely to face [28, 29].

2.4.3 Icebreaker

When parent-daughter teams arrive, there is a sense they are stepping out of their comfort zone and many are visibly nervous. Dedicating 10 minutes is a huge investment in lightening the mood and setting the tone for the event. Many teams may come in with the predisposition that engineering is serious and there is no room for lighter subjects. An icebreaker is a great way for introductions to be made and for attendees to get more comfortable get a better understanding of what to expect from the evening. Foss has observed, it is oftentimes the parents that are most concerned. Parents might worry they won't be able to help their daughter or feel that they don't belong. By starting the evening with an ice breaker, everyone has a chance to connect on a personal level.

Attendees can understand that the goal of the event is to make engineering more approachable and inclusive.

2.4.4 Make it fun

One of the primary objectives of the event is for families to see that engineering is fun and there is a place for women in engineering. Parent daughter teams are not looking for a lecture, they are interested in an activity that will challenge their problem solving and creativity. They also want to be a part of a high-energy and positive environment. This is accomplished in all of the details and the atmosphere that is created by the event organizers. Attention to details such as music, food, t-shirts, and ways to decorate and personalize the design challenge are critical. Each event has a theme that relates to the design challenges as well. For example, during the event in 2017, daughters left the event with a long stem rose. Other events have included decorative gemstones on a photocell electrical circuit jewelry box.

Figures 2.2-2.6 demonstrate the level of detail the staff in the Center of Technology Outreach Office invest in making the event entertaining with a theme, marketing materials, and custom designed t-shirts.

Foss has learned that few attendees are interested in solving calculations and even spending a lot of time in brainstorming or planning. In general, the challenges should be structured to be the most hands-on as possible. Attendees seem to love the building aspect of PJBL methodology and want to focus their energy and time on creating and trouble-shooting instead of designing and planning. While this is counter to the engineering design cycle that engineers use, it is reasonable to save some of the more rigorous aspects of engineering education for post-secondary classes.

Figure 2.2. 2017 Steampunk Theme

Figure 2.3. 2018 Energy Theme

Figure 2.4. T-shirt Design for 2018 event.

Figure 2.5. T-shirt Design for 2019 event.

Figure 2.6. T-shirt design for 2021 event.

2.4.5 Introduce a variety of challenges touching on varied disciplines

Teams often arrive at the event with many preconceptions about what an engineer does and what an engineer looks like. It should be the goal of the event to present the field of engineering in all of its diversity of people as well as roles. While the principles behind the engineering challenges are primarily routed in a PJBL methodology, they should capture various elements of the physical sciences that are applied. Teams will expect the event to be positive and affirming but also interactive and entertaining. In essence, the event should highlight the most exciting and creative aspects of the engineering disciplines.

2.4.6 Guiding the teams that struggle

Some teams may struggle. The parent may have a hard time resisting letting the daughter take the wheel and let her engage in the process. Other parents may feel far out of their comfort zone and as a result become frustrated by their own abilities. The best way to handle these scenarios is with positive encouragement and with probing questions. It is the goal of the event to make engineering more approachable to more people, so introducing too much background information can lead to some teams disengaging from the event. Formulas and calculations introduced need to be at a level that the general public can follow.

Most of the time, the challenges that teams are facing can be remedied with encouragement. Parents need to hear that the design process throughout history is littered with failure and through failure, much is learned. As a result, there is no wrong way and success can be redefined as merely participating in the experience, not necessarily ‘winning’ the challenge. By designing the event based upon PJBL methodology, attendees can gain experience with engineering disciplines in a hands-on and creative manner that is supported by the volunteers and event organizers.

2.4.7 Virtual Setting

In 2020, the event took on a virtual setting. There were several lessons learned from this event that if applied, could make this platform a great way to reach communities that are located farther distances from places of higher education. The key component to make the event successful is prior planning and organizing of challenge materials. For a future event, a secondary school in a rural area could be targeted and the materials could be shipped directly to the school for distribution. Challenges should be designed to use low-cost materials to offset the cost of shipping and should limit the use of supporting materials. There are often support materials that are needed that may not be available, like scissors or glue guns. During an in-person event, scissors are provided for the team tables to use and are retailed for use in future events. It becomes more challenging to include tools like scissors with the challenge materials as it adds to the cost in an incremental way. The solution to this would be to either remove the need for such tools or prepare the challenge materials so cutting is not necessary.

It was also found that the format of breakout groups was not as effective approach to the event. During the first virtual event the group was split into break-out sessions to work on the challenge in a small group. The original idea was that this format would promote engagement between teams, however, the result was a lot of confusion on the part of the parent and daughter teams and limited engagement. The second virtual event kept all the attendees together which made it easier to answer questions that arose as well as for everyone to see what other teams were doing.

2.5 Conclusion

In order to continually advance the field of engineering, more diversity is needed. The role of women in engineering has been historically complex but is also changing in a very dynamic way due to efforts in outreach to all STEM fields in the primary and secondary school systems. Promoting diversity, however, it not so simple and there are many factors that have been discovered in the learning environment that have been shown to increase belonging and decrease stereotyping. The Parent Daughter Engineering night has been designed to capture this research by demonstrating an environment where women and girls are included and thriving in the fields of engineering. By organizing the event to include guest speakers that are students in engineering programs or recent graduates, parents and daughters can more easily visualize a potential pathway as future engineers. By designing the event using PJBL methodology, the engineering field is experienced in an interactive, challenging, and creative way that is also a fun and enjoyable way for a parent and daughter to bond.

Acknowledgements

The Parent Daughter Engineering Night event has been made possible thanks to generous funding from a CTE Perkins grant. The event is made possible thanks to the Center for Technology Outreach and staff including Dana Dellinger, Ana Reyes, Breanna Campbell, Rainie Ingram, Nicole Batty, Dhanya Nair, the WSU student chapter of Society of Women Engineers, College of Engineering, Applied Science, and Technology and Dean Ferro, The Concept Center as well as numerous student volunteers and guest speakers including Elaine Cope, Tammy Patero, Roanna Rague, and The Cookienauts.

References

1. National Science Board. *Science and Engineering Indicators 2016*, Table 2-16.
2. National Science Board. *Science and Engineering Indicators 2016*, Table 2-17.
3. Chen, X. (2013). STEM attrition: *College students' paths into and out of STEM fields.*
4. United States Bureau of Labor Statistics. Labor Force Statistics from the Current Population Survey: Employed persons by detailed occupation, sex, race, and Hispanic or Latino ethnicity, https://www.bls.gov/cps/cpsaat11.htm.
5. M. Inzlicht, T. Ben-Zeev "A threatening intellectual environment: Why females are susceptible to experiencing problem-solving deficits in the presence of males", *Psychological Science, 11*(5), 365–371. 2000. https://psycnet.apa.org/record/2000-00950-003
6. T. Schmader, M. Johns, "Converging Evidence That Stereotype Threat Reduces Working Memory Capacity", *Journal of personality and social psychology*. 85. 440-52. 2003.
7. K. Rainey, M. Dancy, R. Mickelson, *et al.* "Race and gender differences in how sense of belonging influences decisions to major in STEM". *IJ STEM Ed* **5,** 10, 2018.
8. M. Inzlicht, C. Good, "How environments can threaten academic performance, self-knowledge, and sense of belonging", *Stigma and Group Inequality: Social Psychological Approaches*. PP 129-150, 2006
9. M. Inzlicht, T. Ben-Zeev, "A threatening intellectual environment: Why females are susceptible to experiencing problem-solving deficits in the presence of males", *Psychological Science, 11*(5), 365–371, 2000.
10. B. Major, L. O'Brien, "The Social Psychology of Stigma", *Annual review of psychology*. 56. 393-421, 2005.
11. S. Spencer, C. Steele, D. Quinn, "Stereotype Threat and Women's Math Performance", *Journal of Experimental Social Psychology*, Volume 35, Issue 1, 1999, Pages 4-28,
12. C. Good, J. Aronson, J. Harder, "Problems in the Pipeline: Stereotype Threat and Women's Achievement in High-Level Math Courses*", Journal of Applied Developmental Psychology*. 29. 17-28, 2008.

13. D. Quinn, S. Spencer, "The interference of stereotype threat with women's generation of mathematical problem-solving strategies", *Journal of Social Issues*. 57. 55-71, 2001.
14. V. Servant-Miklos, Fifty Years on: A Retrospective on the World's First Problem-based Learning Programme at McMaster University Medical School, *Health Professions Education*, 5(1), 2019, Pages 3-12, ISSN 2452-3011,
15. G. Schmidt, "Foundations of problem-based learning: some explanatory notes", *Medical Education*, 27(5), 1993, 422-432.
16. E. Graaff, A. Kolmos, "Characteristics of Problem-Based Learning", *International Journal of Engineering Education,* 19(5), 2003, 657-662.
17. M. Foss and Y.-C. Liu, "Creating solutions through project-based and experimental learning: A case study of the Concept Center", *International Journal of Engineering Education*, 37(6), 2021, 1630-1642.
18. M. Foss and Y.-C. Liu, "Developing creativity through project-based learning", Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference, virtual conference, April 15-16, 2021.
19. M. Foss and Y.-C. Liu, "Project-based learning center to bridge to students with technology", Proceedings of 2020 Intermountain Engineering Technology and Computing (IETC), Orem, UT, USA, September 2020.
20. M. Foss and Y.-C. Liu, "Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center", Proceedings of the 1st International Academic Conference on the United Nations Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.
21. M. Foss and Y.-C. Liu, "Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines", Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.
22. M. Foss, Y.-C. Liu, and S. Yarahmadian, "Project-based learning in engineering education in a virtual setting: A case study on materials and manufacturing process and applied statistics", *International Journal of Engineering Education*, 38(5A), 2022, 1377-1388.
23. Y.-C. Liu, "Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course", *European Journal of Engineering Education*, 42(6), 2017, 800-811.
24. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
25. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers, "Theo Jansen project in engineering design course and a design example", *European Journal of Engineering Education*, 36(2), 2011, 187-198.
26. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
27. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, "Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course", *International Journal of Mechanical Engineering Education*, 47(4), 2019, 315-337.

28. Y.-C. Liu and F. Baker, "Development of vibration and control system through student projects", Proceedings of ASEE SE Section Annual Conference, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
29. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 8(1), 2018, 1-18.
30. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 7(2), 2017, 106-122.
31. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.
32. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
33. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
34. Y.-C. Liu, J.A. Batte, Z.H. Collins, J.N. Bateman, J. Atkins, M. Davis, D. Salley, C.L. Bethel, J.E. Ball, and C. Archibald, "Mechanical design, prototyping, and validation of a Martian robot mining system", *SAE International Journal of Passenger Car – Mechanical Systems*, 10(1), 2017, 1289-1297.
35. A. Ben-Zeev, et. al. 'Speaking Truth Protects Underrepresented Minorities' *Intellectual Performance and Safety in STEM. Education sciences,* 7(2), 65, 2017.
36. A. Martens, M. Johns, J. Greenberg, J. Schimel 'Combating stereotype threat: The effect of self-affirmation on women's intellectual performance', *Journal of Experimental Social Psychology*, vol. 42, no. 2, pp. 236-243, 2006.

Chapter 3

PJBL Center to Supplement Education

Abstract

The modern engineering profession is dynamic, filled with uncertainty and requires a technical background as well as interpersonal skills. The demands placed on modern engineers are to navigate competing priorities set by clients, regulating bodies, environmental groups, and the public at large to take decisive action to solve the problems faced by industry. For engineering students to be prepared for the challenges they will face in their careers, they need to gain experience working in a dynamic environment to solve projects and problems that diverge from the theoretical realm and enter a practical landscape similar to what they will encounter in industry. One way is through engaging with an on-campus project-based learning (PJBL) center as a student intern. A PJBL Center relies upon a pedagogical strategy where student learning centers around projects under the guidance of faculty mentors. The PJBL Center also functions to allow industry and community partners to engage with faculty and student interns. The Concept Center at Weber State University is modeled after PJBL pedagogy and functions to connect student interns employed at the center with sponsored projects. This chapter discusses the application of PJBL in the Concept Center to achieve a double mission of being an active community member by connecting academia with industry and community members and providing opportunities for students to gain needed skills in problem solving and project engineering. A summary of intrinsic benefits is presented in this chapter with examples of past projects completed at the Concept Center by student interns. Additionally, key

lessons learned from the operation and management of the Concept Center are provided.

3.1 Introduction

Universities are challenged to respond to the needs of industry by preparing students with technical capabilities, intellectual development, and employability skills. This can be accomplished by broadening their understanding to encompass the economic, social, environmental, and international context of their activities [1]. This challenge is also integrated into the accreditation process of engineering programs in the United States [2]. One way to meet this challenge is by supplementing classroom learning with project-based learning (PJBL).

PJBL is a pedagogical approach where the learning centers around problems. The Concept Center at Weber State University is designed as a living laboratory for students to gain hands-on experience through PJBL. The Concept Center strengthens the university's time-tested mission of teaching by expanding that mission to include the conversion of knowledge into solutions to real world problems. The Center employs undergraduate student interns from the College of Engineering, Applied Science and Technology (EAST) in a part-time capacity. Student interns are assigned roles and responsibilities on sponsored projects. These responsibilities and duties include customer relations and communication, product design and development, and manufacturing. Our results from projects completed previously showed that in addition to gaining experience from participating in projects of different nature, students expanded their skills in computer aided design (CAD) software, additive manufacturing technology and other manufacturing methodologies. These student interns will complete their academic careers with skills that are in demand by potential employers. To accomplish this student learning, the Concept Center is organized into two components which represent the mission of the Center:

Education:

The Concept Center is a proving ground for student interns to work on sponsored projects under the direction of faculty mentors. This hands-on experience allows student interns to be better prepared to meet the demands for the modern workforce. By gaining more experience in communication, and broadening their understanding to encompass the economic, social, environmental, and international context of the engineering field, the student intern education is strengthened.

Research and Development:

The Concept Center is a place where new knowledge, technology and capability are constantly being expanded. It can meet a variety of different needs that industry will encounter during their research and development activities ranging from development research to product development. The Concept Center is organized with the following structure shown in Fig. 3.1 to achieve this mission.

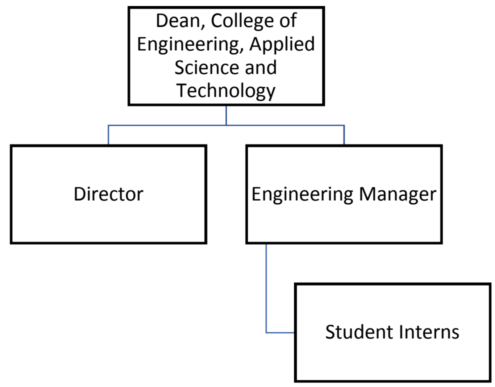

Figure 3.1. Concept Center Organization Chart.

Engineering students need to be prepared with technical capabilities, intellectual development and skills in communication to be able to meet the requirements of industry [1]. Additionally, they need opportunities to hone those skills and incorporate a broader awareness of social, environmental, economic, and legal issues [1, 3]. Student interns employed at the Concept Center get hands-on learning experiences that suitably address these needs.

3.2 Background

PJBL was developed in 1965 by the Faculty of Health Sciences of McMaster University. It is a learning approach in which students solve problems in small groups with the supervision of a tutor for each group [4]. The PJBL process is student-driven, facilitated by the tutor and is based on an educational approach where the learning is driven by problems [5-8]. Learners are encouraged to pursue knowledge by asking questions. PJBL has been regarded as a key strategy for creating independent thinkers and learners in the medical education community [4].

Following the implementation of PJBL in the education of medicine, it has since been expanded to other fields and is considered a solution to some of the issues facing today's engineering education. PJBL was proved to be a successful approach and has been implemented into many engineering academic programs.

For example, the PJBL learning approaches have appreciably facilitated the training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning [6-10]. Liu has successfully integrated the PJBL mode in his senior mechanical engineering classes such as mechanical systems design and vibrations and controls through introducing more than 20 projects from industry partners, university research centers, and a state agency [11-18]. Liu's practice in introducing the PJBL mode into the mechanical engineering classes showed that, by carefully selecting appropriate courses and integrating PJBL into practical capstone experiences, students could supplement theoretical learning with hands-on experience and acquire a set of employability skills. Implementing PJBL in course curriculum strikes a balance between achieving desired student learning outcomes and creating opportunities for enriching the student's educational experience [11-18].

Despite the progress made in integrating PJBL into engineering coursework, there are, however, several major obstacles that hinder a seamless implementation of PJBL into current engineering curriculum [19, 20]. First, students need foundational learning in theoretical principles before these principles can be applied. Textbook problem solving allows students to identify gaps in their content knowledge prior to application as well as provides the instructor an ability to assess the status of individual learning outcomes desired in the course. The time needed to mentor students in a project through PJBL cannot squeeze current instructional time in some foundational courses. Second, most projects have associated costs that require careful planning and budgeting on the part of the instructor. These costs must be secured, allocated and budgeted in advance. If the project is sponsored by industry, the funding source can be the industry partner but this would need to be renewed for each semester in which the course is taught. Integrating PJBL into the curriculum thereby requires a recurring financial commitment that may not be feasible. Thirdly, not all projects fit within the timeline of an academic calendar. This may include a project with a deadline before pertinent topics are taught to the students or a project that may last for multiple years. To facilitate a successful PJBL experience, the time requirements of the project need to match the academic time allocated for the relevant course(s). Lastly, large classrooms can be a challenge for projects that involve prototyping and fabrication. Access to suitable laboratory space and necessary equipment and/or technology may not be feasible for some courses. For example, a large class which cannot physically fit in a laboratory space won't allow everyone in that class to gain the hands-on experience of PJBL.

Despite these obstacles, students can still benefit from the PJBL experience by completing internships through an on-campus PJBL Center. A handful of learning centers were created to facilitate the implementation of PJBL. For example, seven Science, Technology, Engineering, and Mathematics (STEM) centers were created in Texas to deliver professional development activities on STEM education for teachers in district schools [21]. The primary mission of those STEM centers was to design and implement a PJBL pedagogy helping to improve students' readiness for postsecondary majors and professions. Mercer University School of Medicine has a PJBL curriculum with a strong community-based component and a small student body; the PJBL curriculum is mainly implemented through the school's Peyton T. Anderson Learning Resources Center [22]. Samford University started a PJBL center in 1998 to incorporate PJBL into their undergraduate courses and documented the best models of PJBL in their courses [23].

Unlike the previous PJBL centers, the Concept Center at Weber State University is the first PJBL center exclusively established for promoting the implementation of PJBL in engineering education and the Center serves as a hub for various kinds of projects. A student internship with the Concept Center can be a great opportunity to achieve many advantages of PJBL, such as facilitation of training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning. Through the Concept Center, PJBL is incorporated into the academic experience without the constraints of curriculum.

3.3 Benefits of PJBL Center

The Concept Center offers five benefits to the university, faculty, staff, students and the engaged industry or community partners. These benefits are (1) improving the ability to work in an interdisciplinary and cross-functional team; (2) providing an avenue to support and encourage lifelong learning; (3) supporting service responsibility; (4) facilitating student mentoring and; (5) advancing research and education within the university.

3.4.1 Team work in cross functional teams (CFTs)

The Concept Center functions as a hub for engineering projects and design works to be completed by faculty members and student interns across the university. Previous projects completed at the Concept Center led to a number CFTs formed between many academic units across the university, such as different departments in the College of EAST, the Hall Global Entrepreneurial Center, the Office of Sponsored Projects, the College of Nursing, the Department of Zoology, and the Department of Physics, etc. Equipped properly, the Concept Center has the needed infrastructure and design and prototyping capacity for researchers from across the university to come together and form an organizational partnership. Within an organizational setting, a CFT is a common-place and proven structure for businesses to increase competitiveness by leveraging unique skillsets among team members. To support the formation of CFTs, the Concept Center promotes a culture of teamwork by encouraging collaboration instead of competition. This culture is supported through discussing the value of teamwork, rewarding and recognizing teamwork, and modeling teamwork within the Concept Center. A culture of teamwork will encourage faculty members and student interns to work together and combine their skillsets to reach the best solution for the projects. By doing so, the Concept Center can capitalize on CFTs as what has been identified as the main factor in industry to obtain a competitive advantage. As demonstrated by Dinca and Voinescu, six important competitive advantages achieved through this team structure are speed, complexity, customer focus, organizational learning, and single point-of-contact [24].

For example, several recent projects completed at the Concept Center through CFTs include developing and prototyping tactile braille display hardware, devices for monitoring water and air quality, prosthetic guitar pic, and an intubation tool, as well as an aircraft corrosion study. These projects were sponsored either by industry partners or a faculty researcher and required the expertise of faculty members from different academic units. Unfortunately, due to non-disclosure agreements (NDAs) in many of these projects, only limited details can be shared here.

To successfully manage a CFT, it is important to understand the limitations of the CFT and possible reasons that cause failure of certain teams, such as governance, accountability, budgets, etc. [24]. One of the primary roles of the Concept Center is to incorporate this understanding by functioning as a project manager for CFT projects. The CFT projects are managed to be successful by clearly identifying responsibilities of each participating entity and documenting necessary accountability. Failing to establish and document roles of members on the CFT can lead to additional project cost and delay.

3.4.2 Lifelong learning

One of the most important missions of any higher education institution is to nurture and promote a culture in the local community to foster lifelong learning. The benefits of lifelong learning to a community and an individual are immeasurable and that capacity can be developed through the Concept Center. community members ranging from hobbyists to industry partners have clear paths to engage with the university by sponsoring projects via the Center. Some clients of the Concept Center may have little background in technology and design. Through working closely with these clients, the Concept Center will expose them to engineering fields and provide technical support and guidance toward patent application and/or prototype development. Lifelong learning is also promoted in faculty by exposing them to new and unique applications, challenges and technology related to their field of expertise. Student interns have opportunities to interact with customers from different industries and with varying backgrounds and to see the wide application of engineering principles encompassing the projects. Projects completed at the Concept Center also allow student interns and faculty to engage with the local community in a way that is relevant, current, and pertinent to the engineering disciplines. Lastly, student interns, faculty members and clients have an opportunity to continuously develop and evolve their skills in their fields of expertise and can acquire knowledge in areas they were not familiar with before. The result is that the benefits of lifelong learning are achieved for all parties that are involved [25].

3.4.3 Service responsibility

Universities have a moral obligation to serve the communities in which they are located and make efforts to support and promote diversity and equality. This in turn needs to be passed down to the next generation of engineers to recognize the professional duty they have in serving their local communities. The Concept Center at Weber State University addresses this need by engaging in projects that are inherently service orientated. This has been done by funding events through the budget of the Center that are intended to foster and promote community engagement, outreach, or service. The Concept Center also involves in volunteering activities. Those activities include serving as volunteers in outreach events targeting underrepresented minorities. Moreover, student interns are encouraged to take on leadership roles in student chapters of professional organizations such the Society for the Advancement of Materials and Process Engineering (SAMPE) and Society of Manufacturing Engineers (SME). Additionally, the Concept Center has elected to complete many projects pro bono to demonstrate a commitment to service. Such projects include preparing and assembling student supply kits for PJBL engineering outreach events. It deserves mentioning that the Concept Center has an operating budget provided by Weber State University to allow for the purchase of capital equipment and to pay the salary for faculty mentors and wages to student interns. The budget allows for one full-time salaried position that manages the Center. This individual selects appropriate projects and identifies needed faculty and student support for project completion. Funding for student interns work on projects and additional faculty members comes from the budget of the sponsored project

3.4.4 Mentoring

One of the most important benefits of the Concept Center is its inherent mentoring aspect. Student interns are tasked with various roles within an engineering project team under the guidance of at least one faculty mentor. As they progress in the project their skills in analysis, design, research, and problem-solving are further sharpened with the help of the faculty mentor. The benefits of the mentorship are mutual and developmental for both mentors and mentees alike. In that relationship, both parties have opportunities to improve communication and interpersonal skills, develop leadership and management qualities, reinforce study skills and subject-area knowledge, and increase confidence in abilities. In addition, each party will find opportunities to learn and to grow in the areas of creativity, leadership, and professional development

[26]. It also deserves mentioning an explicit benefit to international students whom may not have authorization to work in an industry setting while completing their education. These students can engage with the Concept Center as interns and gain valuable work experience to supplement their learning, thereby completing their education with experience and demonstrable skills.

3.4.5 Advancing research and teaching within the University

Many successful projects completed through the Concept Center have resulted in significant advancements in research or teaching within Weber State University. In these projects, the clients are faculty or staff members of the University who were looking for solutions for their courses or research programs. These projects were previously mentioned in Section 3.1, which include designing and prototyping tactile braille display hardware, devices for monitoring water and air quality, and an intubation tool. A number of teaching aids have also been developed for various courses from these projects. A few examples of the developed teaching aids are Deming's Red Bead experiment for the course Quality Concepts and Statistics in the Manufacturing Systems Engineering (MSE) Department, I-beam molds for laboratory use in the course Reinforced Plastics/Advanced Composites in the MSE department, 3D printed self-assembling bacteria for Introductory Microbiology in the Microbiology Department, Leidenfrost effect blocks for several courses in the Physics Department, and a laser pointer assessment tool for the course Human Anatomy in the Zoology Department. Lastly, three senior project teams in the Mechanical Engineering Department engaged in an autonomous robot competition where each team had to design a robot that would follow a course and launch a projectile at a target from different pre-determined locations. The Concept Center designed and fabricated a table-height 9-foot by 10-foot flat seamless surface equipped with side barriers and target locations that could be easily stored compactly when not in-use.

3.5 Examples of Projects

A review of recent projects completed at the Concept Center of Weber State University is helpful to demonstrate the diversity and complexity of the projects that support the benefits of PJBL as elaborated in Section 3. However, many projects completed at the Center cannot be fully described because they are subjected to NDAs. Four projects that do not subject to any NDA are presented here as examples to demonstrate the unique and diverse learning experiences achieved through PJBL at the Center.

3.5.1 Solar Pavilion

The goal of the Solar Pavilion project was to design and fabricate two solar powered pavilions equipped with lighting and charging sources to power electronic devices. The primary goal of this project was to provide a safe and attractive place for students to convene, study, and work together outside. There were no such areas for students on the campus at that time and the cost of installation to run a new power line to a remote part of the campus was prohibitive and against the campus goals of sustainability. This project was selected by the Concept Center due to its scope that linked to curriculum topics including project management, applied topics in materials science, manufacturing processes, design, and control systems and ABET criterion student outcomes 1, 2, 5, and 7.

This project was left uncompleted by a faculty member who left the university prior to its completion. The Concept Center agreed to complete the project with funding from the Office of Facilities Management. The project team was composed of 4 undergraduate student interns and 2 faculty mentors. After an initial review, the team quickly realized that most of the work that had been done previously was not usable. The original design included a mechanical structure that would be cost prohibitive to fabricate and might lead to safety issues.

Many projects in industry change hands due to various reasons. This makes it imperative for the new project team to stay open-minded about the best way to proceed. In the case of this project, a significant investment in hardware (batteries, structural steel, and power inverters) had been made by the previous team. It would be tempting for any team to design a solution by taking advantage of what has already been purchased but oftentimes, such decision can result in the project not meeting customer requirements. Previous decisions made in projects are based on information or technology that was current at that time and might no longer be the best option. In this project, the purchased batteries were nearly depleted; the structural steel was intended to protect the batteries but was not corrosion resistant; and the power inverters were undersized. When inheriting an uncompleted project from another team, the new team needs to review design rationale and verify if it is consistent with the customer needs. This type of learning experience is difficult to simulate in a classroom setting.

The evaluation of the original design also allowed the team to better identify the problem, which is another valuable learning experience intrinsic to PJBL. The original design had an umbrella-like pavilion but did not include requirements for resistance to wind forces and snow load. The original design is shown in Fig. 3.2. As shown in that figure, batteries were designed to be stored in steel boxes under seats. However, structural analysis of the pavilion was missing. After reviewing the original project documentation, the team redefined major tasks for this project: (1) design and build a corrosion resistant structure that meets local building codes, (2) design and build a solar power station capable of charging portable electronic devices, and (3) design and build a structure with a solar-powered lighting source.

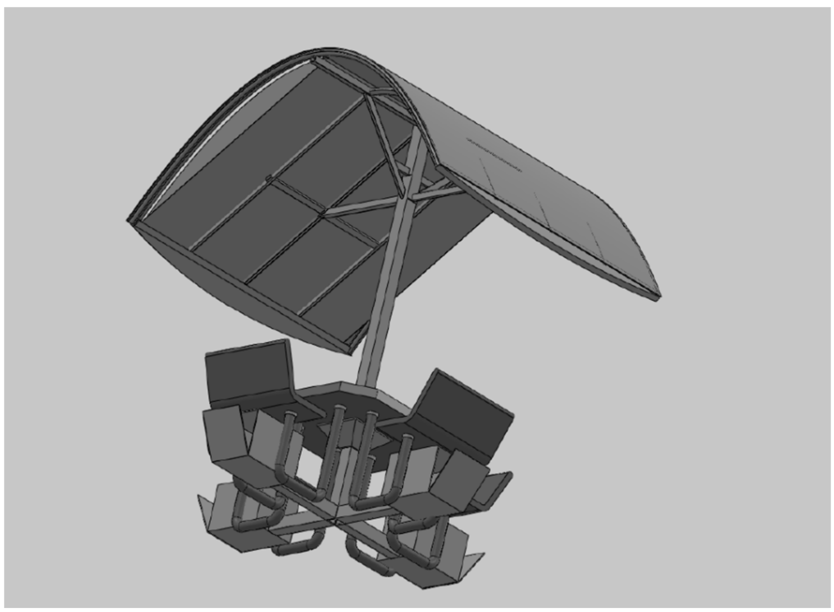

Figure 3.2. Original computer-aided design of solar pavilion

This project also offered valuable learning experiences in project management. Fabrication and installation of the solar pavilion required the Office of Facilities Management to dig footings. Due to the commitment of this office to other priorities, this portion of the project had a 6-month lead-time, during which the progress on the project was stalled. During the lead-time, the team completed work on different concurrent projects while waiting for the completion of the footings. Student interns are typically assigned multiple project assignments to simulate what they would encounter in an industrial setting. This gives student interns experience in multi-tasking as well as managing multiple projects concurrently to build skills in project management.

At the completion of this project, two solar pavilions were installed on campus. Student interns gained hands-on experience in design and fabrication of the corrosion-resistant metal structures and accompanying solar power lighting and charging stations. In carrying out this project, they also developed skills in troubleshooting, teamwork, and problem solving. One completed solar pavilion with a student user is shown in Fig. 3.3. The pavilions have been in operation since June of 2019. The Concept Center has been monitoring their performance since then and has verified from student feedback that the solar powered pavilions function well in providing outdoor charging access for students. In recognition of the team's efforts, the project team was invited to a formal luncheon organized by the Office of Facilities Management.

Figure 3.3. Completed solar pavilion

3.5.2 Cadaver Storage System

The Zoology Department at Weber State University received two cadavers by donation for use as teaching aids. A faculty member in that department wanted to use these cadavers in undergraduate human anatomy courses but did not have a way to store them. Moreover, the department did not have a budget or funding access to purchase a cadaver storage system. Laboratory grade cadaver storage systems are quite costly with a unit price as high as $15,000. The Zoology faculty member approached the Concept Center for help with a temporary and a long-term storage solution for the cadavers. A team including 4 student interns and 2 faculty mentors was formed to conduct this project. Based on the customer's requirements, the team began by dividing this project into two phases. The goal of the first phase was to provide a short-term solution for the summer term and the goal of the second phase was to develop a long-term solution for permanently storing the cadavers in the Zoology Department. This project was chosen by the Concept Center because the scope allowed for the application of topics related to the engineering curriculum including engineering design, materials science, manufacturing processes, statics and strengths of materials as well as FEA analysis and control systems. ABET Criterion 3 student outcomes 1, 2, 3, 5 and 7 were also addressed.

The goal for phase 1 was identified as to create a temporary storage system that would eliminate required daily maintenance for the cadavers during the summer. The gurney that was in use required application of preservation fluids every day to prevent the cadavers from dehydrating and becoming damaged. Since the summer months were only a few weeks away when this project commenced, this became a unique opportunity for student interns to derive a temporary solution with a low budget and tight time constraint. Such a situation is one where creativity and problem solving become the most important skills. With these constraints, the team came up with a temporary solution that would only cost about $100 for the summer term. A custom fabricated wooden storage container with a polymer impermeable liner was built for the phase 1. This container functioned perfectly through the summer of 2019 and did not require any maintenance treatment during that time. The customer, a zoology faculty member, expressed satisfaction with the wooden storage container delivered by the project team.

In phase 2, the team was given enough time to design a cadaver storage system to permanently meet the need of the Zoology Department by following a systematic engineering design process implemented in a senior design class at another institution in the United States [12-15, 17-18]. Design requirements of this project were first identified after reviewing defects of existing commercial products. The team found that existing products on the market are less ideal for intermittent usage by faculty and students. In commercial cadaver storage systems, 1% phenoxyethanol is used as a wetting agent and is delivered through either manual spray or immersion tank. Manual spraying requires constant maintenance and would take considerable time of the instructor. Immersion tanks are a compromise between long-term storage and teaching versatility. In addition to their high price, immersion tanks require the removal of the cadaver from the immersion tank 24 hours prior to usage to allow for preservation fluids to drain from the cadaver. Additionally, immersion tanks are bulky in size and extremely heavy. To eliminate those defects, the design requirements were defined as: (1) the cadaver storage system should have the ability to combine an automated fluid spray and recycling system with the current cadaver gurney tables, (2) the cadaver storage system should be easily moved and (3) each cadaver storage system should cost less than $6,000.

The team presented a design that modifies the existing cadaver gurney table by adding an automatic spray system supplied by a recirculating reservoir. This spray system is controlled by a timer with a manual override, eliminating the need for the instructor's manual maintenance and fluid drain time. Additionally, by eliminating the large immersion tank, the storage system is more compact. The modified gurney table design simplifies the wetting efforts while retaining the automated tilt and elevation functions of the gurney table for ease of teaching. The total cost for designing and fabricating two such storage systems was $11,050. The cost requirement of this project is therefore met.

CAD models of this design and its automatic spray system are displayed in Figs. 3.4a and 3.4b, respectively. The difference in cost over the purchase of a system on the market largely is due to the utilization of an existing cadaver gurney. In addition to its low cost, the designed spray system features a significant weight reduction compared with the immersion tank. This design also eliminated the need for expensive structural materials capable of handling the loading and environmental requirements of an immersion tank.

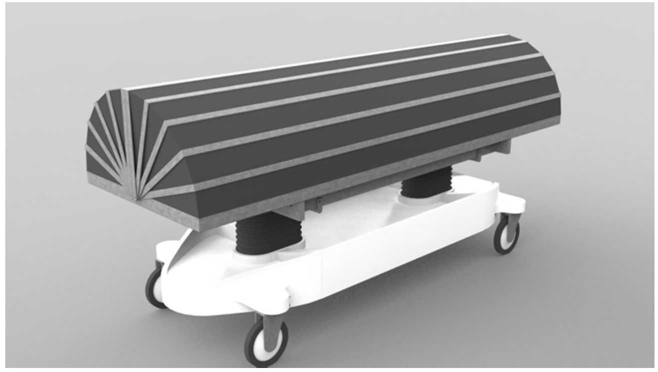
Figure 3.4a. A CAD model of the cadaver storage system


Figure 3.4b. A CAD model of the automatic spray system

The designed cadaver storage system is currently being fabricated but the project has already produced several positive outcomes:

1) The CFT (including faculty mentors and student interns from departments of Zoology, Mechanical Engineering, and Manufacturing Systems Engineering) was awarded a grant of $11,050 from the University to fabricate the cadaver storage system.
2) Major work and main results of this project have been presented at the 2019 Human Anatomy and Physiology Society (HAPS) conference by a student intern.
3) One student intern highlighted this project experience on his resume and received a full-time job offer upon graduation from a laboratory equipment company as a design engineer.

3.5.3 Public Art Project

A unique project with a goal of creating a public art sculpture for a faculty member from the Visual Arts Department was undertaken by the Concept Center. In conjunction with the College of EAST, the faculty artist assisted in hosting a summer camp titled 'The Art and Science of Metalwork' for high-school aged girls [27]. This project was selected by the Concept Center due to its scope links to curriculum in manufacturing processes as well as ABET Criterion 3 Student Outcomes 3 and 4.

During this summer camp, 16 high-school aged girls spent three days on-campus learning about welding and metalwork. They completed a total of six projects during the camp. One of those projects was for each girl to write a Haiku poem. The text of these poems would later be cut into pickets for a fence for a public art project displayed at the Bountiful Davis Art Center in Bountiful, Utah (Fig. 3.5). Utilizing CAD tools, two student interns at the Concept Center designed panels with poems on them. The developed CAD models were then imported into a computer numerically controlled (CNC) waterjet cutter for making the haiku fence pickets. Student interns learned how to program and operate this waterjet cutter to fabricate the pickets from participating in this project.

Figure 3.5. Completed haiku fence [28]

Besides this public art project, student interns were assigned with several other tasks in support of other camp projects, which included materials preparation, assisting the girls in welding technique, and maintenance of the metal inert gas (MIG) welders such as replacing damaged contact tips. Student interns were also trained on programming and operation of the CNC plasma cutting table and gas settings on the MIG welders.

3.5.4 Mold for mannequin shoulder teaching aid

One of many ways the PJBL Center supports the university is through recognizing and supporting the university’s mission of teaching. The Concept Center has completed many projects of developing teaching aids for faculty members to use in their classes. One such project was the development of a mold for a mannequin shoulder insert. A faculty member from the Department of Zoology wanted a mold that could be used to make gel shoulder inserts for a mannequin for a continuing medical education (CME) accredited class for the Ogden Surgical-Medical Society’s 2018 annual meeting. The gel shoulder inserts would be used in a technical training course for attendees led by a faculty member from the University. The mold was designed to allow attendees who are doctors, nurse practitioners, and physician assistants to practice injecting corticosteroids into various joints of the shoulder that are prone to damage. In this technical training course, CME students could visually see the location where the dye was delivered to simulate an injection of medicine on a real shoulder. The faculty member approached the Concept Center and asked help for fabricating such a mold. The mold would allow him to produce the shoulder inserts and eliminate the need of purchasing one from a third-party vendor. This project was selected by the Concept Center because its scope included concepts learned in the classroom including mold making and materials science and addressed ABET Criterion 3 Student Learning Outcomes 1 and 2.

The Concept Center formed a small team of one student intern and one faculty mentor to carry out this project. Using the mannequin provided by the Zoology faculty, the team made a reusable silicon mold. Fig. 3.6 shows the mold made in progress for the mannequin shoulder. The student intern acquired a skillset in making the mold from this project and the final mold prototype only costed $180. This mold allowed for the fabrication of multiple shoulder inserts for the students who attend the CME class to practice repeatedly. A similar product on the market is a single-use arthroscopic shoulder with a unit price of $255.

Figure 3.6. Mannequin shoulder mold teaching aid in progress

3.6 Lessons Learned in Identifying Appropriate Projects

Successful projects have several key qualities in common which are important to recognize when evaluating whether a potential project should be taken on and will ultimately lead to a beneficial experience for the student interns, faculty mentors, and customers. Projects must be evaluated in the context of the mission of the Center while considering the capacity of the student interns and faculty mentors affiliated with the Center. In general, an approach of under-promising and over-delivering is a safe way to communicate capabilities, resulting outputs, and timeframes with the customers. Key factors to consider are highlighted below:

3.6.1 Intrinsic learning to student interns and faculty

Before moving forward with any project, one question that needs to be answered is will the project bring valuable learning opportunities? Several projects have not progressed beyond the initial customer meetings because they would not promote student learning. One such project was to fabricate metal lawn signs to promote an event. This project was not chosen by the Center because it did not have a design component and would offer limited opportunities for teamwork, collaboration, design, experimentation, or acquisition of new knowledge to the student interns and faculty. Projects that are undertaken by the Concept Center should present a strong design, research, or fabrication challenge and not be primarily assembly work.

3.6.2 Incremental stretch of skillset or capability

The Concept Center must evaluate the stretch required on existing skillsets or existing infrastructure and equipment for completion of projects. By considering if the skills required for the project are attainable or if the complexity of the project is beyond the scope that can be handled by the faculty and student interns, projects can be evaluated as suitable or unsuitable. This is a very subjective measurement but should be taken before starting a project. For instance, the Concept Center did not take on a material characterization project for a medical device company because the requirement of conducting this project surpassed the capacity of the Center. This project involved testing material samples and providing resulting data that would be used for a medical device submission change to the Food and Drug Administration (FDA). However, since the Center is not an ISO 9001 certified laboratory, the data generated from the Center would not be considered valid and therefore not be usable, so the project was not undertaken.

3.6.3 Well defined scope of work

A project with a vaguely defined scope and deliverables is difficult to conduct and can result in unsatisfactory results that fail to meet the customer needs. At the initiation of each project, there must be a clearly defined statement of work that details work that will be completed, along with deadlines and costs. This document needs to be reviewed and approved by both the Concept Center and the client so that it will serve as a legally binding agreement. Many conflicts and misunderstandings can be avoided by properly and explicitly defining the project's scope of work and specifying responsibilities, deliverables, and tasks that will be completed during the project period.

3.6.4 Flexible time constraint

Projects with tight time constraints can be a recipe for disaster. When determining the project duration, the team needs to account for the extra time needed to provide quality mentoring in addition to allowing for unexpected situations that result in delay. One such project that did not proceed past the scoping phase was an industry partner looking for help with hardware design for an aircraft. In this project, the customer required full-time employment and required the project to be completed in two months, which is unrealistic for a student project managed by the Concept Center, and therefore this project was declined.

3.6.5 Customer's ability to recognize the value of learning

It is most helpful if customers approach the Concept Center with an understanding of the value of PJBL to the students and a supportive and cooperative attitude. In one example, a customer refused to provide engineering drawings of a prototype and only wanted the Center to fabricate mass quantities of the product off a CAD file. Without reviewing the geometric dimensioning and tolerance (GD&T) requirements of the product, the faculty and student interns would not be able to evaluate the suitability of candidate manufacturing methodologies. This customer did not even allow student interns to review the design and manufacturing plan, which is customary in the planning phase of a project and offers a valuable learning opportunity for student interns. Engaging with this type of customer is not recommended.

3.6.6 Feasibility

It is quite common for the Center to receive many proposals presenting infeasible projects. Some customers assume that a project can be completed by student interns without associated costs. Other customers think that engineering design and analysis does not require a certain amount of labor time. There are still a few customers who have unreasonable ideas about fundamental laws of science. Many projects failed to progress beyond initial meetings because the customers imagined that there should be no costs associated with the work on design, research and prototyping. Other projects could not be carried out because the science background of the customers was so flawed that their ideas violated laws of physics and could never be turned to realities. In one example, faculty engaged with the Center were exploring a project with a local industry partner. After completing three meetings and two tours of facilities, the industry partner insisted that student interns would be working for free, which is not the format for projects at the Concept Center unless there is a clear service component of the project. To avoid significant time invested into these kinds of projects, it is sagacious to utilize a project application form as a screening tool. This form will be completed by potential customers and should include information such as the description of the project, customer requirements including cost, time, materials, and other specifications. If available, the customer can supplement the application form with engineering drawings. This form will become a starting point for the Center to assess the suitability and feasibility of the project. It also can form a baseline for additional questions raised toward the project to finalize its scope and required deliverables. If the project appears to meet the requirements described in sections 5.1 to 5.5, the Center will arrange an initial project meeting with the customer.

In the initial meeting, a discussion of an estimated budget for the project is appropriate in addition to reviewing customer expectations. In some cases, the customer may not have a technical background and may have not done any vetting of the project in terms of practicality or may assume there is no cost associated with the project. In these instances, it is very likely that misunderstanding between two parties appears. Customer meetings should be summarized with meeting minutes where details of the discussion and future plans or actions are explicitly stated. These meeting minutes should be shared with the project team and the customer. It is also imperative that the communication back to the customer about failing to accept the project is with utmost respect.

It should be noted that the Concept Center has had several experiences in which customers failed to answer follow-up questions related to their project. If the customer is not responsive in the early stages, this may be a sure indication that the project should not be accepted. In this case, it is still important to close the communication to the customer with an explanation why the project is no longer under consideration.

3.7 Lessons Learned in Student Intern Management

To ensure project success and build a positive reputation for the Center and the University, it is critical that a competent team of capable faculty members and student interns is formed for each project. Key factors to consider in forming such a project team and the resulting organizational structure are highlighted in following subsections.

3.7.1 New student interns are employed in a project-based capacity

The Concept Center employs student interns for each new project based on the alignment between the project requirements and the students' background. This project-based hiring helps to engage students with the Center without a long-term commitment. For example, to fabricate the cadaver storage system in phase 2, the team needed a stainless-steel welder. Since the MSE Department has a program with emphasis on welding engineering, the team contacted that department and successfully hired a student from the department with professional welding experience. The MSE student joined the project team during the fabrication phase and then resumed his outside employment after completing his task in that project.

There are situations in which it can become quickly apparent that an intern will not be successful in the project team. In one example, a new student intern was assigned a project task and given a deadline for completion. The intern failed to do any work and did not show up to the Center. To keep project schedules moving, it may be necessary to reassign projects to different students and remove students from project teams. However, considering the many experiences a PJBL center can offer, formal intern dismissal should be avoided if possible. The project-based hiring is also a way of simulating a 90-day probationary period that new employees would normally have in their company, which makes the formal dismissal of a student intern unnecessary.

Dismissing an intern should only happen in extreme cases of gross negligence or due to illegal behaviors.

3.7.2 Proven interns are employed in a continuous capacity

Some of the most notable gains that can be attained through PJBL are achieved with continued mentoring. Student interns that have demonstrated their ability to learn, engage, and function in a team can be employed with a regular weekly schedule in a continuous capacity and be assigned multiple projects with long timelines. The regularly scheduled hours can be designed to accommodate the student's course load and could vary from 10 to up to 30 hours per week and extend through semester breaks. These student interns are funded through the budget of the center. This continuous involvement allows for student interns to build working relationships with their faculty mentors and with other student interns and get involved in a diverse number of projects and multiple project teams. For example, one such student intern was employed through the Concept Center for two years. Throughout this time, he worked on a total of 14 different projects. The hours he worked were set on a schedule that was designed to accommodate his course load and were increased during semester breaks. This format allowed for continued mentoring until his completion of his degree program and entry into industry.

3.7.3 Professional development for students

The Concept Center is committed to promote the professional development of the student interns. Major activities include supporting the students to attend conferences, expos, and other events relevant to their field of study. For example, the student interns have attended the Wasatch Front Materials Expo, Society for the Advancement of Materials and Process Engineering (SAMPE) monthly meetings, The Composites and Advanced Materials Expo (CAMX), and Western States International Council on Systems Engineering (INCOSE) conference. Student interns are also encouraged to take on internships provided by industry partners and other companies. For example, one intern employed by the Center was offered a summer internship by a laboratory equipment company in another city. With the overall goal of supporting students to advance in their careers after graduation, the student intern was welcomed to return to the Concept Center at the completion of the summer internship when the semester commenced.

3.7.4 Facilitate recruitment of student interns

One challenge that a PJBL center faces is to recruit top students for the projects. The high-ranked students often have other opportunities with internships from local industry employers. At most universities, the stipend paid to undergraduate students is not competitive with what is offered by industry employers. To recruit more high-ranked student interns, it is critical to explain to them the benefits of the project experience to their careers and assign them project tasks that best match their interests and which they can take advantage of in pursuing their career goals.

3.7.5 Allow for individualized mentorship

Student interns can benefit the most from the PJBL center through the mentoring relationship. From a mentoring standpoint, each student will have varying and individual needs. One student may need instructions on research methodologies.

Another student may need guidance in interpersonal and communication skills. It is the responsibility of the mentor to assess the needs of each student intern and guide them accordingly. The role that the mentor plays should be tailored for each student intern. Each mentor should meet with student interns individually, document their goals of development, and discuss ways of assessing their progress.

Faculty mentors should utilize failure of the student interns as opportunities for their growth. Positive learning experiences often result from failures if those failures are managed delicately. For example, one student intern sought to take all credit for project work and neglected to recognize the roles of other team members. It should be the responsibility of the mentor to use this as a lesson to educate the student intern to understand the negative influence on team culture from such behavior. Through these practices, the student interns will grow professionally and be better prepared for their careers.

The number of student interns that the Concept Center can support is greatly influenced by the number of mentors available as well as the number of projects, scope of the projects, and operating budget. Potential projects should not be undertaken without adequate mentors with appropriate backgrounds and expertise. To ensure quality mentoring, the mentor must spend a considerable amount of time with each student intern while managing the project toward its completion. Full-time faculty mentors affiliated with the Concept Center feel that they can successfully manage up to 5 direct reports. Capacity of each mentor must be considered when assigning student interns to this mentor to ensure that each student intern will have a positive experience from working in the project team and from the mentorship program.

3.8 Conclusion

The modern engineering profession is dynamic and constantly changing. To be better prepared for engineering careers, students nowadays need more experience and opportunities to learn outside of the classroom. A PJBL center like the Concept Center is an effective way to educate and train current students for the demands placed on modern professionals to navigate competing priorities set by clients, regulating bodies, environmental groups, and the public at large. It also can function as a platform to engage industry partners and community members with faculty and student interns through mutually beneficial R&D activities. This chapter shares the experience of the Concept Center at Weber State University in establishing PJBL learning models. The benefits of a PJBL center to the students, faculty members, and the institution are fully demonstrated. Examples of past projects are reviewed, and lessons learned from those projects are discussed. By overcoming the challenges posed by the institution, the customers, and the projects themselves, the Concept Center is making progress toward its mission of connecting academia with industry and community sponsors. Projects completed demonstrate the ability of the Concept Center to address the expressed needs of the projects while providing excellent opportunities for student interns to gain crucial problem solving and employability skills.

Acknowledgements

This chapter is authored based upon projects completed at the Concept Center at Weber State University located in the College of EAST. The authors would like to express their gratitude for the help and support from the following student interns, faculty members, and staff: Thomas Odenwalder, Brandon Burke, Taylor Foss, Dr. David Ferro, James Taylor, Justin Knighton, Patrick Thomas, Gina Naisbitt, George Comber, Jason Manley, Jeff Strahan; and industry and community sponsors: Hill Airforce Base, Murphy Door, ATK, Hydropur, GSC Foundries, Dr. Brian Chung, and SES Engineering.

References

1. *The Green Report: Engineering education for a changing world*, American Society of Engineering Education, Washington DC, 1994.
2. *Criteria for Accrediting Engineering Programs*, Engineering Accreditation Commission of the Accreditation Board of Engineering and Technology, ABET, Baltimore, Maryland, 2001.
3. J. Mills and D. Treagust, Engineering Education – Is Problem-Based or Project-Based Learning the Answer? *Australian Journal of Engineering Education*, **3**(8), 2003, pp. 2-16.
4. G. Schmidt, Foundations of problem-based learning: some explanatory notes, *Medical Education*, **27**(5), 1993, pp. 422-432.
5. E. Graaff and A. Kolmos, Characteristics of Problem-Based Learning, *International Journal of Engineering Education,* **19**(5), 2003, pp. 657-662.
6. Y.-C. Liu, Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course, *European Journal of Engineering Education*, **42**(6), 2017, pp. 800-811.
7. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers, Theo Jansen project in engineering design course and a design example, *European Journal of Engineering Education*, **36**(2), 2011, pp. 187-198.
8. Y.-C. Liu and Y.-Q. Dou, Design of an industry-tied and team-oriented course for mechanical engineering seniors, *Proceedings of ASEE SE Section Annual Conference*, University of Florida, Gainesville, FL, April 12-14, 2015.
9. S. Bell, Project-Based Learning for the 21st Century: Skills for the Future, *The Clearing House*, **83**(2), 2010, pp. 39-43.
10. J. Uziak, A project-based learning approach in an engineering curriculum, *Global Journal of Engineering Education*, **18**(2), 2016, pp. 119-123.
11. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course, *International Journal of Mechanical Engineering Education*, **47**(4), 2019, pp. 315-337.
12. Y.-C. Liu and F. Baker, Development of vibration and control system through student projects, *Proceedings of ASEE SE Section Annual Conference*, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
13. Y.-C. Liu, V. Meghat, and B. Machen, Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an

engineering systems design approach, *International Journal of Design Engineering*, **8**(1), 2018, pp. 1-18.

14. Y.-C. Liu, V. Meghat, and B. Machen, Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach, *International Journal of Design Engineering*, **7**(2), 2017, pp. 106-122.
15. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.
16. Y.-C. Liu, J. A. Batte, Z. H. Collins, J. N. Bateman, J. Atkins, M. Davis, D. Salley, C. L. Bethel, J. E. Ball, and C. Archibald, Mechanical design, prototyping, and validation of a Martian robot mining system, *SAE International Journal of Passenger Cars – Mechanical Systems*, **10**(1), 2017, pp. 1289-1297.
17. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
18. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
19. J. Perrenet, P. Bouhuijs, and J Smits, The Suitability of problem-based learning for engineering education: theory and practice, *Teaching in Higher Education*, **5**(3), 2000, pp. 345-358.
20. I. Rios, A. Cazorla, J. Diaz-Puente, and J. Yague, Project-based learning in engineering higher education: two decades of teaching competences in real environments, *Procedia Social and Behavioral Sciences*, **2**(2), 2010, pp. 1368-1378.
21. S. Han, B. Yalvac, M. M. Capraro, and R. M. Capraro, In-service teachers' implementation and understanding of STEM project based learning, *Eurasia Journal of Mathematics, Science & Technology Education*, **11**(1), 2015, pp. 63-76.
22. J. H. Labeause, LibQUAL+™ in a problem-based learning (PJBL) medical school, *Journal of Library Administration*, **40**(3-4), 2004, pp. 59-72.
23. S. Ahlfeldt, S. Mehta, and T. Sellnow, Measurement and analysis of student engagement in university classes where varying levels of PJBL methods of instruction are in use, *Higher Education Research & Development*, **24**(1), 2005, pp. 5-20.
24. L. Dinca and C. Voinescu, "Cross-functional teams and their role in increasing competitiveness of the organizational partnerships", *Proceedings of European Integration Realities and Perspectives*, **7**, 2012, pp. 453-459.
25. M. Laal and P. Salamanti, Lifelong learning; why do we need it", *Procedia - Social and Behavioral Sciences,* **31**, 2012, pp. 399-403.
26. W. Hart, In focus/mentoring nurturing relationships provide many benefits", *Leadership in Action*, **29**(1), 2009, pp. 17-20.
27. M. Cortez, *Weber State's Girls Welding Camp harnesses 'power of lightning*, https://www.deseret.com/2018/7/12/20648917/weber-state-s-girls-welding-camp-harnesses-power-of-lightning#emily-curtis-welds-during-girls-welding-camp-the-art-

science-of-metalwork-at-weber-state-university-in-ogden-on-tuesday-july-10-2018, Accessed April 15, 2020.

28. J. Manley, *Haiku Fence Detail*, https://www.jasonmanley.com/?attachment_id=631, Accessed April 15, 2020.

Chapter 4

Developing Creativity Through PJBL

Abstract

Engineering students must be prepared to enter a profession that is dynamic, filled with uncertainty and requires a technical background as well as interpersonal skills. The demands placed on modern engineers are to navigate competing priorities set by clients, regulating bodies, environmental groups, and the public at large to take decisive action to solve the problems faced by industry in new and oftentimes, unexpected ways. Of all the demands placed upon engineers, creative problem solving is quite possibly the most abstract as well as most critical in success. For engineering students to be prepared for the challenges they will face in their careers, they need to gain experience working in a dynamic environment to solve projects and problems that diverge from the theoretical realm and enter a practical landscape similar to what they will encounter in industry by developing experience and skills in creative problem solving. One way is through engaging with an on-campus project-based learning (PJBL) center as a student intern. A PJBL Center relies upon a pedagogical strategy where student learning centers around projects under the guidance of faculty mentors. The PJBL Center also functions to allow industry and community partners to engage with faculty and student interns. The Concept Center at Weber State University is modeled after PJBL pedagogy and functions to connect student interns employed at the center with sponsored projects. This chapter discusses the application of PJBL in the Concept Center to achieve a double mission of being an active community member by connecting academia with industry and providing

opportunities for students to gain needed skills in creative problem solving. A summary of examples of past projects completed at the Concept Center by student interns that function to support the development of creative problem solving is presented.

4.1 Introduction

Engineering Education is continuously changing and improving. As noted by Felder, the format of learning via lecture-homework-quiz is an efficient way to present a lot of information in a condensed amount of time, however, though it functions well to impart facts to students, it does not necessarily prepare students to solve problems [1]. Furthermore, the Green Report published in 1994 by the American Society of Engineering Education (ASEE) was a call for change to respond to the revolutionary change that was taking place in technology. In this report, the authors challenged academic institutions to respond to the needs of industry by preparing students with technical capabilities and intellectual development but also with skills in communication, and broadening their understanding to encompass the economic, social, environmental, and international context of their activities [2]. This call was loud and clear and is now integrated into the accreditation process of engineering programs in the United States [3].

The concept of creativity is abstract as well as difficult to assess much less define. While researchers from behavioral psychology, social psychology, cognitive science, design research, innovation, philosophy and others might differ in an exact definition of what it is to be creative, there is more of a general agreement about traits and qualities that define a creative person. In Kazerounian and Foley's research, creativity is summarized as an intrinsic quality defined by the ability of a person to take chances; to make unique connections between ideas; to be flexible and imaginative; to question ways of doing things; and to be motivated, inquisitive as well as intuitive [4]. Recognizing the lack of scholarly research in the study of creativity in engineering education along with some alarming research by Wilde that showed that engineering education in fact can decrease creativity [4, 5], Kazerounian and Foley identified ten maxims of creativity in Education which are seamlessly addressed through the pedagogical framework of Project-Based Learning (PJBL) through an on-campus internship such as the Concept Center at Weber State University.

4.2 Background

The Concept Center at Weber State University is designed as a living laboratory for students to gain experience through PJBL [6-10]. The Concept Center supplements the university's time-tested mission of teaching by expanding that mission to include the conversion of knowledge into solutions to real world problems thereby allowing students to apply the theoretical concepts they have learned. The Center employs undergraduate student interns from the College of Engineering, Applied Science and Technology (EAST) in a part-time capacity. Student interns are assigned roles and responsibilities on industry sponsored projects. These roles include customer relations and communication, product design and development, and manufacturing. In addition to gaining experience with a variety of projects, students develop and utilize learned skills in computer aided design (CAD) software, additive manufacturing technology and other manufacturing methodologies [10]. These graduates will complete their academic careers with skills that are in demand and relevant to today's job market. Achieving this goal requires two components which represent the mission of the Center:

Education:

The Concept Center is a proving ground for student interns to work on industry sponsored projects under the direction of faculty mentors. This hands-on experience allows student interns to graduate better prepared to meet the demands of the modern workforce by gaining more experience in communication, and broadening their understanding to encompass the economic, social, environmental, and international context of the engineering field.

Research and Development:

The Concept Center is a place where new knowledge, technology and capability are constantly being expanded. It can meet a variety of different needs that industry will encounter during their research and development activities ranging from traditional research to product development.

PJBL was developed in 1965 by the Faculty of Health Sciences of McMaster University. It is an approach to learning in which students solve problems in small groups with the supervision of a tutor [11-13]. It has since been widely accepted in the education of medicine and is thought to be a solution to some of the issues facing today's engineering education and has been implemented in some settings. PJBL is based on the educational approach where the problem is the starting point of the learning [11-13]. The PJBL process is student-driven, and facilitated by the instructor. Learners are encouraged to pursue knowledge by asking questions. PJBL is regarded as a key strategy for creating independent thinkers and learners in the medical education community [12].

The PJBL learning approaches have resulted in the facilitation of training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning [14-22]. One author (Liu) has successfully integrated the PJBL mode in his senior mechanical engineering classes such as mechanical systems design and vibrations and controls through introducing more than 20 projects from industry partners, university research centers, and a state agency [14-16, 18, 19].

4.3 The Ten Maxims of Creativity in Education and PJBL

Kazerounian and Foley identified ten maxims of creativity based upon a large body of literature on creativity as well as their own experience to assess the ability of engineering education to meet these needs [4]. This list was created by Kazerounian and Foley as a starting point of a compilation and culminating result that educators can refer to. This section will demonstrate that PJBL is a useful tool in addressing each of these maxims by providing examples from the Concept Center. Many of the projects discussed are subject to non-disclosure agreements (NDAs) with the customer, so limited details can be shared here.

4.3.1 Keep an Open Mind

Creativity can be taught by learning to see things in a new light. Often, the best answer is not the most obvious. In one project, the Concept Center was working with a company that needed a solution to improve the aesthetic aspects of a latch system for their product. The Concept Center initially worked to completely redesign the product and pursued three different design concepts each significantly resulting in a more complicated and expensive solution. Eventually, the team reexamined the goals of the project and reframed it to create and design a housing to obscure the unattractive latch system. This proved to be a simple and inexpensive solution that the customer could mass-produce. By keeping an open mind on the project, the team was easily able to abandon the overall direction of the project and refocus on other alternative solutions.

4.3.2 Ambiguity is Good

For Foss, this maxim is probably the most challenging for engineering students. Students are used to being fed problems with neatly defined constraints as well as given variables. Problems encountered in industry tend to instead be not well-defined and inherently ambiguous. Many students are uncomfortable spending time defining the problem and tend to want to start working on the solution whether the problem is adequately defined or not. Student interns are intentionally tasked with a vague problem which needs to be better developed and defined before a solution can be identified. This process allows for the opportunity of discovery and innovation as it slows down the pace in the early stages of the problem definition and allows students to research and collect information before focusing on the solution. In one example, a customer approached the Concept Center to make an athletic tape dispenser product for a student that only had one arm. The product needed to accommodate multiple rolls of athletic tape as well as have the ability to cut the tape at custom lengths with one-handed operation. The Concept

Center began by looking for solutions that could meet the customer requirements and created a simple and low-cost prototype that was belt-mounted and used a cutting wheel and slider as well as an easy quick-release mechanism for changing and replacing tape rolls. Though, initially this project was defined with very limited requirements from the customer, the ambiguity allowed for the team to fully understand and explore the functional requirements and create a simple and inexpensive solution.

4.3.3 Iterative Process that Includes Idea Incubation

Creativity can occur in stages and time must be allowed for the process to be complete. Allowing a project to sit on a "back burner", can lead to more creative solutions. However, for obvious reasons, idleness is not encouraged. For this reason, student interns at the Concept Center are often assigned multiple projects. Not only does this simulate the work environment he or she will experience in industry, but it also allows for the delay in task progress that results in benefiting creativity [23]. Multiple projects not only function to aid students in developing skills in project management and multi-tasking, but also allows for idea incubation.

4.3.4 Reward Creativity

With positive reinforcement and reward, creative and innovate solution can be recognized. This creates an environment which allows for students to strive for and target innovation as an objective. With any problem considered in PJBL, there is no right answer, but rather a series of options that need to be carefully considered and evaluated to select the best of all the possible answers. Rewards that have been offered at the Concept

Center include everything from recognition in the form of a luncheon to a gift card and in one instance a $1,000 scholarship. It is also worth noting the intangible reward of creativity of experience and resume building for student interns. Student interns have reported back to Concept Center management that their experience with PJBL has allowed them to discuss unique and interesting examples during the interview process of their job search. Former student interns ascribe their experience with the Concept Center as beneficial in making them stand out to potential employers.

4.3.5 Lead by Example

In Taylor's work on climate for creativity, he described the observation of a colleague, "As I am hearing these things and as I reflect upon people who have done something that has truly reshaped the world, nearly all of them have gotten outside of existing organizations to do so" [24]. Taylor then mused that perhaps traditional and conventional organizations as a model might in fact be functioning to hinder creative scientific work. It is possible that the common thread that links organizations together in their ineffective efforts to spur creativity is not leading by example nor believing that a creative solution exists. A culture in which ideas are quickly dismissed will greatly hinder the brainstorming process. Foss is known to use the history of the 4-minute mile as an example of the power of what people can do if they believe they can do it [25]. To reap the benefits of PJBL in creating innovative solutions, it is imperative that an environment is created where leaders 'practice what they preach,' believe in the process, and lead by example.

4.3.6 Learning to Fail

Fear of failure can be paralyzing and functions to greatly hinder what anyone can accomplish. At the Concept Center, student interns make frequent errors in design and analysis and assumptions. However, rather than using these errors as reason for discipline, instead they can be reframed to allow for a deeper understanding of the topic which can in turn lead to innovation. If students understand why their concept does not work, they can be better able to identify other concepts that might work. Many students have not had the opportunity yet to build the resiliency needed to move beyond failure and see it as merely a pathway to their end goal, so it is important to communicate with them that many of the greatest accomplishments throughout history are a direct result of failure [26]. In one example, a student intern selected a circulating pump intended to circulate a specialized fluid. The pump was tested upon arrival and found to be inadequately sized. In this example, allowing the student to make a low-risk mistake can function as an incredible learning opportunity. The pump was inexpensive and could be returned but allowed for the student to grow in understanding of fluid systems as well as become more thorough in selecting components for an assembly. Learning to fail is a skill like any other and ultimately allows for engineers to make mistakes and learn from those mistakes without becoming debilitated by the error.

4.3.7 Encouraging Risk

Encouraging sensible risk taking for student interns to pursue ideas that are not likely to be successful is something that must be intentional in a PJBL Center. Often, student interns have a limited understanding and experience with technology and there is a gap between what is believed is possible and what has historically been possible. The

Concept Center has mentored students that have proposed solutions to problems that would likely defy laws of science. However, with proper coaching, these ideas can often evolve into something else that is innovate as well as possible. By allowing students to take risks with their time and research they can go down paths that would not have been considered and potentially identify a new and innovate way of examining the problem. In one example a customer tasked the Concept Center with designing a system that could melt snow from a driveway. The customer described frustration with shoveling snow and identified a marketing opportunity for a product that would not involve demolition and instead could be installed on the surface of an existing driveway. The student intern team initially considered a very complicated hydraulic system. Intuitively, the Concept Center management believed the economics of such a project would be prohibitive but encouraged investigating this project nevertheless. Ultimately, the team identified several potential methodologies and built a scaled prototype based upon roof melt heating technology. The prototype was delivered to the customer for testing. While the results of the testing were unsatisfactory, the customer was satisfied with the initial prototype and is currently engaging with the Concept Center to look at design revisions.

4.3.8 Search for Multiple Answers

Classical tools in brainstorming can be used to generate creative solutions. The Concept Center structures projects so that students work in teams. Teams dedicate the early stages of projects in brainstorming multiple solutions. In one example, in the early stages of the COVID-19 pandemic, all in-person intern work was halted and the Concept Center transitioned into a virtual work environment. As a result, much of the hands-on and fabrication aspects of the Center were put on hold and attention was redirected to projects that could be done remotely. One such project that the student intern teams elected to complete was to identify current technology that could be used to clean and disinfect surfaces and environments. By brainstorming and understanding the unique environments of Weber State University and the needs of various computer labs, metal cutting lab, welding lab, and other large work places, the students were able to search for multiple solutions divided by applications such as the heating, ventilation and air conditioning (HVAC) system, impervious and non-impervious surfaces as well as potential designs for no-touch handles into the buildings and classrooms. By utilizing the brainstorming process, they were able to identify many recommendations to the multi-faceted problem and document them in a report.

4.3.9 Internal Motivation

Creativity is supported through PJBL when students are interested in the project and motivated by the challenge of the project. The Concept Center addresses this by aligning projects with the personal interest of the interns when possible. For example, one such intern has a background in the Navy working on a submarine and has a passion for nuclear power generation. While there were no current sponsored projects available to assign to him related to nuclear power, he was instead assigned a project in renewable energy examining the use of solar power for emergency use in marine applications. While ultimately, the conclusion of his work was that size requirements of solar power were prohibitive for the application, this served to be a good way for him to expand his interest in alternative energies and build upon his interest in nuclear power.

4.3.10 Ownership of Learning

Students are better able to explore creative and innovative solutions when they have control over the project and a sense of ownership. This personal investment in the project can allow them to develop a sense of pride as well as satisfaction in the tangible aspects of their work. In one example, a student intern worked directly with the customer on a project to build a cadaver storage system. The customer was a faculty member of Weber State University and built a relationship and rapport with the student and invited him to attend and present his work at a conference [6]. The student was very engaged with this project due to the level of ownership he had that resulted from him being the primary point of contact with the customer. As a result, he was not only able to design a cost-effective solution to the problem but also develop a sense of pride in the work he was doing.

4.4 Conclusion

The modern engineering profession is hinged upon creative problem solving. To prepare students for careers in engineering, they need more experience and opportunities to learn outside of the classroom and develop skills and confidence in creative thinking. A PJBL Center is one way to better prepare students for the demands placed on modern professionals to navigate sometimes competing priorities set by clients, regulating bodies, environmental groups, and the public at large. The wide variety of projects that student interns are exposed to illustrates the ability of a PJBL Center to achieve its mission and address the 10 maxims of creativity. A PJBL Center connects academia with industry and provides an opportunity for students to gain needed skills in creative problem solving.

Acknowledgments

This chapter is based upon projects completed at the PJBL Concept Center at Weber State University supported by the College of Engineering, Applied Science and Technology. The authors would like to express their gratitude to the student interns, faculty members, and staff involved (Thomas Odenwalder, Brandon Burke, Joshua Lepus, Austin Byrer, Kaitelyn Whiting, Jacqueline Fessler, Nathaniel Pope, Taylor Foss, David Ferro, James Taylor, Justin Knighton, Gina Naisbitt, George Comber).

References

1. R. Fleder, "On Creating Creative Engineers". Engineering Education, 77(4), 222–227 (1987).
2. American Society of Engineering Education, "The Green Report: Engineering education for a changing world". *ASEE*, Washington DC, (1994).
3. ABET, "Criteria for Accrediting Engineering Programs". *Engineering Accreditation Commission of the Accreditation Board of Engineering and Technology*, Baltimore, Maryland, (2001).
4. K. Kazerounian, S. Foley, "Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions". *Journal of Mechanical Design*, 129, 2007.
5. D. J. Wilde, 1993, "Changes Among ASEE Creativity Workshop Participants," J. Eng. Educ., 82(3), 167–170.
6. M. Foss and Y.-C. Liu, 2021. "Creating solutions through project-based and experimental learning: A case study of the Concept Center", *International Journal of Engineering Education*, 37(6), 1630-1642.
7. M. Foss, and Y.-C. Liu, 2021. "Developing creativity through project-based learning", *Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference*, virtual conference, April 15-16, 2021.
8. M. Foss and Y.-C. Liu, "Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center", Proceedings of the 1st International Academy Conference on the Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.
9. M. Foss and Y.-C. Liu, "Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to

Engineering Disciplines", Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.

10. M. Foss and Y.-C. Liu, "Project-Based Learning (PJBL) Center to Bridge Students with Technology," *2020 Intermountain Engineering, Technology and Computing (IETC)*, Orem, UT, USA, 2020, pp. 1-5.
11. J. Mills, D. Treagust, "Engineering Education – Is Problem-Based or Project-Based Learning the Answer?" *Australian Journal of Engineering Education*, 3(8), 2003.
12. G. Schmidt, "Foundations of problem-based learning: some explanatory notes". *Medical Education*, 27(5), 1993, 422-432.
13. E. Graaff, A. Kolmos, "Characteristics of Problem-Based Learning", *International Journal of Engineering Education,* 19(5), 2003, 657-662.
14. Y.-C. Liu, "Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course", *European Journal of Engineering Education*, 42(6), 2017, 800-811.
15. Y.-C. Liu, et al., "Theo Jansen project in engineering design course and a design example", *European Journal of Engineering Education*, 36(2), 2011, 187-198.
16. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, April 12-14, 2015.
17. S. Bell, "Project-Based Learning for the 21st Century: Skills for the Future", *The Clearing House*, 83(2), 2010, 39-43.
18. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, "Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course", *International Journal of Mechanical Engineering Education*, 47(4), 2019, 315-337.
19. Y.-C. Liu and F. Baker, "Development of vibration and control system through student projects", ASEE SE Section Annual Conference, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
20. J. Uziak, "A project-based learning approach in an engineering curriculum", *Global Journal of Engineering Education*, 18(2), 2016. 119-123.
21. J. Perrenet, P. Bouhuijs, J. Smits, "The Suitability of Problem-based Learning for Engineering Education: Theory and practice", *Teaching in Higher Education*, (5)3, 2000, 345-358.
22. I. Rios, A. Cazorla, J. Diaz-Puente, J. Yague, "Project-Based learning in engineering higher education: two decades of teaching competences in real environments". *Procedia Social and Behavioral Sciences*, 2(2), 2010, 1368-1378.
23. J. Shin, A. Grant, "When Putting Off Work Pays Off: The Curvilinear Relationship Between Procrastination and Creativity", Academy of Management Journal, 0, 2020.
24. C. Taylor, Climate for Creativity: Report of the Seventh National Research Conference on Creativity. Elsevier. 2013
25. J. Daley, "Five things to Know about Roger Bannister, the First Person to Break the 4-minute Mile", Smithsonian Magazine, March 15, 2018.
26. C. Mueller, "*Creativity in Science: Fostering Failure*," *Potomoc Institute: Science, Technology, Engineering, and Policy Studies*. [online journal]. URL: http://www.potomacinstitute.org/steps/component/content/article?id=18:creativity-in-science-fostering-failure [retrieved March 25, 2021].

Chapter 5

PJBL Virtual Settings

Abstract

This chapter details the case-study of incorporating project-based learning through a virtual materials characterization project. This project exposes students to characterization technology, manufacturing processes, data analysis and the application statistical tools. Moreover, by utilizing the project-based learning methodology, students develop skills in teamwork, oral and written communication, and problem solving that do not come from the back-of-the-book. In the present case study, material properties of a pair of failed multipurpose crafting shears labeled as 'stainless' are characterized. The student teams are challenged with identifying the manufacturing process that was used based on the data acquired from metal spectrometer testing, Rockwell C hardness testing, and scanning electron microscope (SEM) imaging of the failure surface of the sample. Based upon the analysis of this data, students are tasked with identifying the type of metal alloy for the crafting shears, the manufacturing process used, and possible root cause of failure. This case study provides a pedagogical framework to bridge concepts of materials science with manufacturing methodology and statistical analysis tools as well as creative thinking and problem-solving skills. By investigating and determining the root cause of failure the students have gained a better understanding of the relationship between manufacturing process, material properties, and product quality. The outcomes could be used directly in an existing course, since all the data have been provided or it could also be adapted for different contexts by replacing the existing data with a new data set.

5.1 Background

Understanding how student learning is accomplished is fundamental in developing course curricula to accomplish learning outcomes. As the Nobel Laureate in the field of cognitive science Herbert Simon said, "Learning results from what the student does and thinks and only from what the student does and thinks. The teacher can advance learning only by influencing what the student does to learn."

Research suggests that problem-based learning (PJBL) is a successful and innovative method for engineering education [1, 2]. Learning outcomes can be achieved by exposing students to project work with key characteristics: theoretical principles of the problem analysis, knowledge and practice integration, collaborative group work, and real-world problems [1, 2]. To better prepare students to meet the demands of modern and future industry, engineering curriculum needs to include and focus more on skills that are difficult to assess in a classical examination or problem-solving format. One way to do this is by incorporating Project-based Learning (PJBL) challenges within the curriculum. These challenges are cross-disciplinary in nature. PJBL has similar pedagogical elements to PJBL but compared with PJBL, PJBL tends to entail multiple subjects, is longer in duration (weeks or months), follows general steps, results in the creation of a final product (report), and often utilizes real-world scenarios [3].

PJBL was developed in 1965 by five Health Sciences faculty members led by John Evans, the founding Dean of McMaster University Medical School [2, 4]. It is a learning approach in which students solve problems in small groups under the supervision of a tutor [4]. The PJBL process is driven by the students, facilitated by their tutor, and is based on an educational approach where the learning is driven by problems or can be thought of as “learning through application”. In this approach, learners (students) are encouraged to pursue knowledge by asking questions. PJBL has been regarded as a key strategy for creating independent thinkers and learners in the medical education community [3-6].

Following the implementation of PJBL in the education of medicine, it has since been expanded to other fields and is considered a solution to some of the issues facing today’s engineering education [5]. For example, faculty at Weber State University established a PJBL center to achieve a double mission of being an active community member and providing opportunities for engineering students to gain needed skills in problem solving and project management [6-11]. It has been found that the PJBL learning approaches greatly facilitated the training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning [12-14]. Liu and coworkers successfully integrated the PJBL mode in senior mechanical engineering design classes by introducing more than 20 projects from industry sponsors, university research centers, and a state agency [12, 14-16,19-24]. Working on those projects in teams effectively enhanced the students’ capacity in solving problems of industrial relevance. It was found from Liu’s practice that the implementation of PJBL in course curricula struck the balance between achieving desired student learning outcomes and creating opportunities for enriching the student’s educational experience [14-17].

One cross-disciplinary topic that is critical in mechanical engineering education is the quality of final products, which represents an intersection between product design, manufacturing process, and materials science. Engineering students need to understand how the quality and performance of a final product are affected and influenced by these factors. Understanding the mechanisms and modes of failure in an engineering product is crucial in evaluating its quality, design approach, and development process. For students to better understand these interactions, it is helpful to engage them in projects that incorporate each of these areas so that the collective effect can be better understood. Often it is difficult for beginning mechanical engineering students to bridge course contents and see how different course topics relate to design and fabrication of quality products. This chapter presents a PJBL challenge that can be incorporated in a virtual setting to allow students to investigate and identify the material properties, manufacturing processes, and causes of product failure. Presented as a case study, this chapter highlights the assessment of a failed product, analysis results, and student recommendations for future design improvements of the failed product. Using a common product as a case study is an effective way for students to gain experience in the application of materials science principles, manufacturing processes, and statistical analysis tools to assess the product quality and determine the cause of failure. By utilizing statistical analysis tools, Rockwell hardness testing, spectrometer testing, and scanning electron microscope (SEM) imaging, students are challenged to determine the role of materials, manufacturing process and design on the ultimate failure of a product or component.

5.2 Step 1: Project Description

In this project, a class of 30 students divided into teams of 5 students were presented with images of a pair of failed crafting shears as shown in Figs. 5.1 and 5.2.

Their task is to investigate the shears based upon the given images and deduce the materials of the shears and their manufacturing process.

Figure 5.1. Failed crafting shears used for a PJBL case-study.

Figure 5.2: Product labeling, where the word "stainless" is visible.

5.3 Step 2: Hypothesis and Assumptions

Based upon the labeling in Fig. 5.2, students may assume that the shears were made of a stainless steel. With this assumption and the assigned course resource materials, students may conclude that the stainless steel was selected due to its inherent mechanical properties such as hardness and corrosion resistance and hypothesize that the material is a 400-series martensitic stainless steel. This type of stainless steel offers excellent corrosion resistance due to the natural chromium oxide layer formed on its surface. That layer also has superior hardenability, a necessary property needed to maintain a sharp edge [25, 26]. The only product labeling is shown in Fig. 5.2 and clearly states “Stainless Pakistan”. Based on that labeling, students may deduce that the product was made of a stainless steel and is capable of long-term use and performance.

Based on the material, students may hypothesize a manufacturing process that was employed to fabricate the shears. A high-quality tool made from a high-performance material such as stainless steel would require an appropriate manufacturing process in order to achieve the optimal microstructure of the material, which leads to the best material properties and desired performance of the finished product. Students may hypothesize that a forging operation was applied to produce discrete parts of the shears by shaping the stock material with compressive forces through various dies and tooling. This manufacturing process would allow workers to control the metal’s grain structure and result in a finished product with good strength, toughness, as well as other properties required for high stress applications. Following the forging process, a machining process would be carefully selected to process the stainless steel to achieve the desired dimensional accuracy, which is followed by grinding and polishing to achieve sharp edges capable of shearing raw materials [25, 26].

Finally, students are tasked with hypothesizing the root cause of the failure of the product after evaluating the images provided and based upon their assumptions of materials and manufacturing processes. Moreover, since the material labeling contains the country of origin of this tool, the students are encouraged to investigate potential manufacturers in Pakistan and determine the one that made this tool. Students will then be asked to validate their hypothesis and assumptions through a series of experiments.

5.4 Step 3: Failure Imaging and Analysis

To examine the fractured surface of the shears, SEM was applied to produce high magnitude and high-resolution images, as shown in Figs. 5.3-5.7. Before the shears were observed under the SEM, a diamond, water-cooled cutting blade had been used to remove a section of material from the shears that was of a suitable size at the failure site. The sample was then sputtered for 30 seconds to clean the fractured surface without compromising the sample. The sample was then put under the SEM to record the fracture surface photographically.

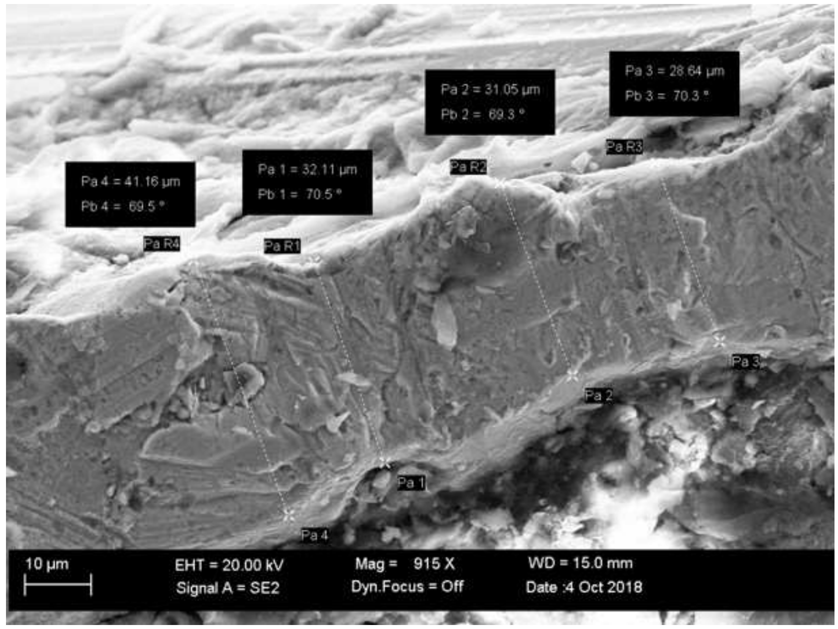

Figure 5.3. SEM of a surface layer (martensitic structure)

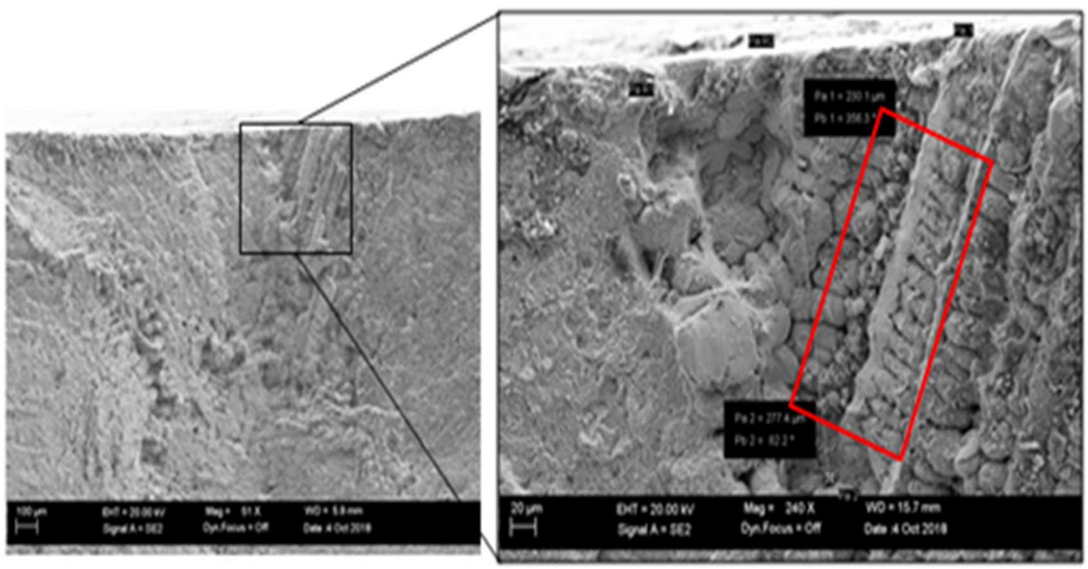

Figure 5.4. Dendrites on fracture surface (rectangular region)

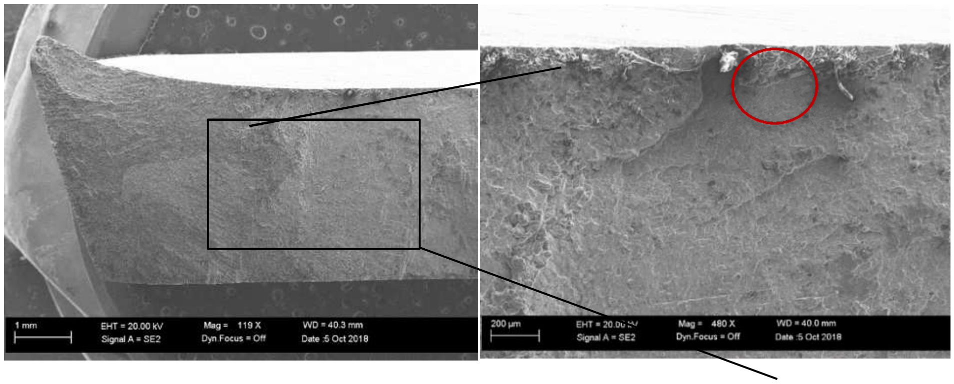

Figure 5.5. Fracture initiation site with cleavage planes (circled)

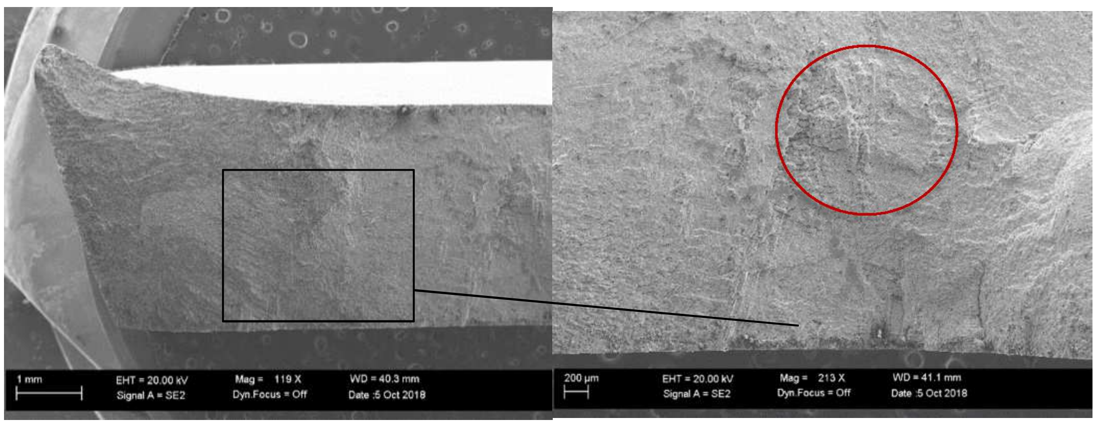

Figure 5.6. SEM image of the bottom edge of fracture surface showing porosity (circled)

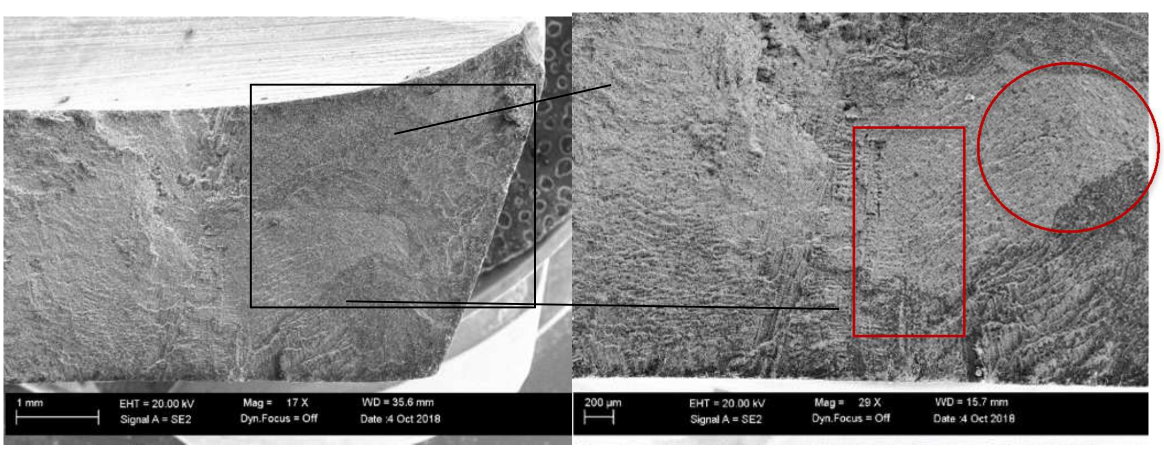

Figure 5.7. SEM of the edge of fracture surface showing cleavage planes (circled) and dendritic structures (rectangular region)

Upon initial examination of the fractured surface of the shears, students will not see any evidence of failure from ductile fracture or fatigue. Students will instead see evidence of a martensitic structure as shown in red in Fig. 5.3. The martensitic structure could allow for brittle fracture of the material.

Another feature that the SEM images show is dendrites highlighted in Fig. 5.4. Dendrites are tree-like structures, formed by crystallization while the molten metal freezes. The presence of dendrite structures is evidence of rapid material cooling. Rapid material cooling would cause the generation of martensitic crystal structure that would exhibit less than expected mechanical properties (material failure under normal use) and be likely to fail in a brittle manner [25].

Fig. 5.5 was taken on the fracture surface. In this imaging, the potential fracture initiation site can be seen as a large cleavage plane and the porosity within the material can be visually confirmed via the presence of many voids that are indicated as dark shaded areas. Fig. 5.6 represents the opposite side of the fracture surface and shows evidence of another potential crack initiation site originating from the surface as well as extensive porosity. Fig. 5.7 also shows evidence of additional dendritic structures, along with cleavage planes.

Based upon these images, students can make following inferences:

- The material failed in a brittle manner based upon the presence of large cleavage planes.
- The material exhibited a martensitic microstructure.
- Dendritic structures provided evidence of rapid material cooling.

- Porosity existed in the material.

5.5 Step 4: Material Characterization and Analysis

Students are introduced to characterization techniques through a virtual demonstration and provided the characterization data and images upon completion. Techniques utilized are Rockwell C hardness testing, metal spectrometer testing, and SEM imaging. Through this activity, students are introduced to technologies used to characterize materials as well as limitations in those technologies.

5.5.1 Rockwell C Results and Analysis

Rockwell C hardness testing was performed at first following a procedure described by Reeves et al. [27]. In measuring the hardness (represented by HRC values) of this material, the Rockwell-C hardness machine was first calibrated using a standard sample with a known hardness of 62.2 HRC. Next, two test samples were taken from the blades of the crafting shears, which are labeled as A1 and A2 (Fig. 5.8). These samples were then mounted to a testing fixture to hold the specimens in place and polished to remove the surface finish. Fig. 5.8 shows the location of the test samples and Fig. 5.9 shows the fixtures that hold the specimens with indentions generated from the hardness tests labeled.

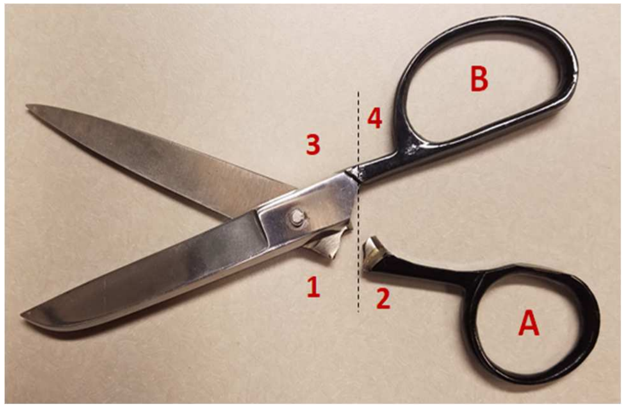

Figure 5.8. Different parts of the crafting shears are labeled for use in hardness testing (A1 and A2)

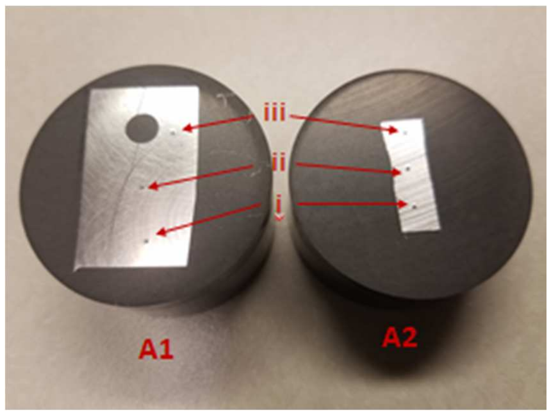

Figure 5.9. Specimens after the Rockwell C hardness test labeled as A1 and A2 and i to iii indicate the locations at which the hardness test was performed

The results from the Rockwell C hardness test are displayed in Table 5.1.

Table 5.1. HRC values measured from the two specimens

Location	HRC Value
A1- i	50.1
A1- ii	57.9
A1- iii	62.5
A2 – i	54.4
A2 – ii	52.9
A2 – iii	56.8

Average	55.77

There are several potential learning outcomes from the analysis of the Rockwell C hardness data. Students are tasked with utilizing statistical tools to understand what conclusions can be drawn from analyzing this data set.

Students will complete a statistical analysis and one sample T-test on the data set. The T-test results are listed in Table 5.2 (CI means confidence interval).

Table 5.2. One sample T-test results of the Rockwell hardness data

$\boldsymbol{\mu}$, Mean	Standard deviation	95% CI for $\boldsymbol{\mu}$ (min)	95% CI for $\boldsymbol{\mu}$ (max)
55.7	4.32	51.24	60.30

Based upon these results, students will understand that hardness testing only provides limited information. Students may conclude that these values do not allow for a conclusive material characterization as such results would be expected in a number of different alloys [25, 26]. Limitations of hardness testing can be better understood by calculating the number of samples that should be taken for statistical basis, n. This analysis does demonstrate to students that more testing is required to fully characterize materials than hardness testing alone. In general, hardness testing is helpful as an inexpensive and quick test but the results are insufficient for accurate material characterization.

5.5.2 Spectrometer Analysis Results

A Spectromaxx LMM04 spectrometer was used to determine the mass percentages of all chemical elements within the crafting shears. The spectrometer was calibrated using a standardized steel specimen with a pre-known composition. To prepare the shears for testing, a large portion of the blades were cut and polished to remove the surface finish. Three samples were taken at the locations indicated in Fig. 5.10.

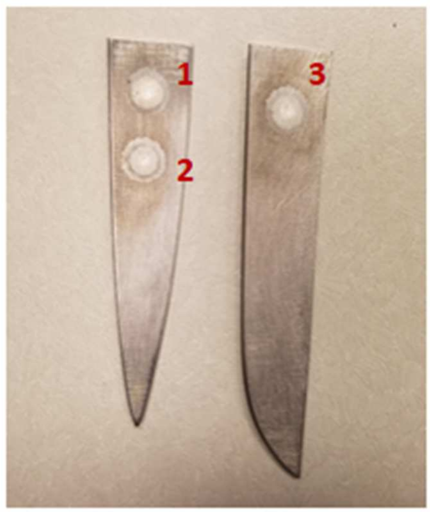

Figure 5.10. Samples were taken from three different locations on the blades for spectrometer testing

The spectrometer results from 3 different tests (Table 5.3) were used to characterize the material of the product. The average results of the 3 different tests are also listed in Table 5.3.

Table 5.3. Spectrometer testing results

	% C	% Si	% Mn	% P	% S	% Cr	% NI	% Mo	% Al
	0.86	0.98	0.317	0.026	0.021	7.82	0.2	0.035	0.0043
	0.95	1.02	0.32	0.022	0.027	7.49	0.188	0.035	0.0053
	0.75	1.18	0.283	0.025	0.021	8.63	0.182	0.037	0.0057
Average	0.8533	1.0600	0.3067	0.0243	0.0230	7.9800	0.1900	0.0357	0.0051
	% Cu	% Co	% Ti	% Nb	% V	% W	% Pb	% Mg	% B
	0.133	0.016	0.0011	0.012	0.016	0.045	<0.002	0.0029	0.0023
	0.136	0.01	0.0014	0.011	0.015	0.047	<0.002	0.0029	0.0026
	0.139	0.017	0.0011	0.016	0.016	0.026	<0.002	0.0035	0.0028
Average	0.1360	0.0143	0.0012	0.0130	0.0157	0.0393	<0.002	0.0031	0.0026

5.5.2.1 Spectrometer analysis: Carbon content

Carbon is the most important element in commercial steel alloys. Increasing carbon content increases hardness and strength and improves hardenability of steels. However, as carbon content increases, the steel will become more brittle and more difficult to weld because of the carbon's tendency to form martensite. Thus, to predict the properties of the material, its carbon content needs to be determined first.

Several issues can be discussed based on the spectrometer testing results. Firstly, students will be directed to perform a statistical analysis of the data from Table 5.3. Using the statistical software, Minitab, students can create a graphical summary report of the data as shown in Fig. 5.11.

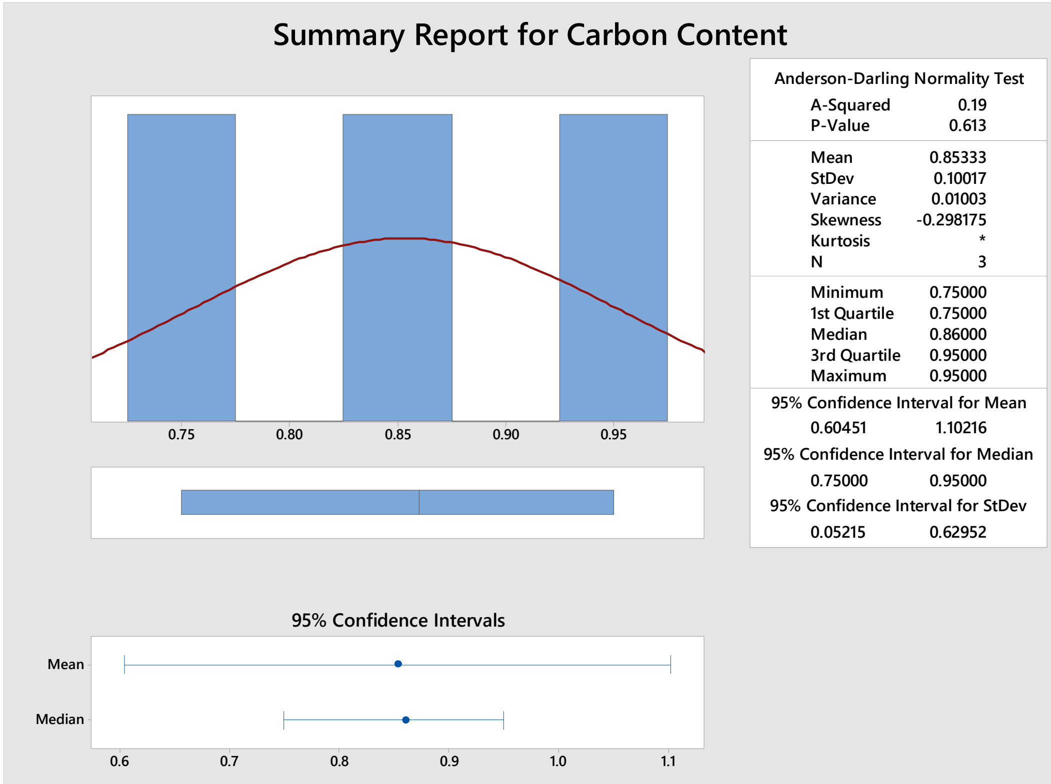

Figure 5.11. A graphical summary of carbon content

Upon reviewing that figure, students can conclude that the variation present in the carbon content is high. The results of a one sample T-test give a 95% confidence interval, which is quite broad and overlaps two categories of alloy steels (medium and high carbon steel) with a potential mean of 0.60451% to 1.10216% as shown in the graphical summary. Carbon content representing bulk properties of the material is expected to have a much lower standard deviation.

Students should be encouraged to understand the cause of the variation present in the carbon content. Upon reviewing the test procedure, students should make the following observations: 1) A small amount of the polished surface was removed prior to performing the spectrometer test. 2) The amount of material removed is inherently variable in the three different locations as shown in Fig. 5.5. This would contribute to the variations in the surface depth of each sample. 3) Due to the nature of how this test was performed, it is plausible that the data represent the surface properties of the shears and not the bulk material properties [25, 26]. Students can then be encouraged to investigate the manufacturing processes that might lead to the change in the surface properties. The case hardening process is a possible explanation for the inherent variation of surface concentration of carbon at different depths.

Utilizing a simple and cost-effective case hardening method such as pack carburization, carbon diffuses in accordance with Fick's Law into the microstructure of the material. As the depth of the material from the surface increases, the amount of carbon present is known to decrease. Surface carbon content can reach upwards of 1% at the surfaces but at depths on the order of 10^{-4} mm, the concentration quickly reduces to 0.75% and eventually levels out to the bulk properties of the material [28].

With an understanding of the case hardening process, students may conclude that the large variations present in the spectrometer results is in fact due to the inherent variations caused by the case hardening process and the testing location depth. Those results do not represent the mass percentages of the chemical elements in the bulk material. This hypothesis aligns well with the data gathered by Schneider and Chatterjee from their hardening tests which shows typical case depths of 1.5 mm [28].

5.5.2.2 Spectrometer analysis: Manganese content

Manganese is a key component of stainless-steel and medium and high carbon alloy formulations. In fact, in many stainless steels and medium and high carbon alloys, the manganese content is found to be 0.6% or even higher [29]. The manganese content detected by the spectrometer ranges from 0.283% to 0.320% (Table 5.3), which is well below what would be expected to be present in a stainless steel or medium or high carbon steel. The max 95% confidence interval for the mean shown in the one sample T-test results in Table 5.4 (0.3577%) also confirms the material is not a stainless steel nor medium or high carbon steel grade since it is well below an expected value of 0.6%. By eliminating the stainless-steel grades as well as the medium and high carbon alloy grades, the low manganese content suggests that this material must have a low carbon content and further reinforces the theory that a case hardening process was applied to increase the surface concentration of carbon. However, further testing of the bulk material would be required to confirm this inference since the spectrometer results only reflect the surface properties [25, 28, 29].

Table 5.4. One sample T-test descriptive statistics of the Mn content

$\boldsymbol{\mu}$, Mean	Standard deviation	95% CI for $\boldsymbol{\mu}$ (min)	95% CI for $\boldsymbol{\mu}$ (max)
0.3067%	0.0206	0.2556%	0.3577%

5.5.2.3 Spectrometer analysis: Silicon content

The presence of other alloying elements at high percentages is also of interest when attempting to fully characterize this material. One interesting element detected by the spectrometer is silicon. Table 5.5 shows the statistical analysis results of the silicon content.

Table 5.5. One sample T-test descriptive statistics of Si content

μ, Mean	Standard deviation	95% CI for μ (min)	95% CI for μ (max)
1.066%	0.1058	0.7971%	1.3229%

Students will be required to understand what inferences can be made from the present data. Silicon as an alloying element in steels increases strength, hardness, and corrosion resistance but to a lesser extent than manganese. Usually only small amounts of silicon (~ 0.20%) are present in steels but the quantities of silicon detected by the spectrometer are clearly higher than that level, which range from 0.98% to 1.18%. Since the silicon level in the material is high and exhibits a large variation as shown in the results from a one sample T-test (Table 5.5), it can be deduced that this element was not alloyed into the material. This will lead students to evaluate potential manufacturing processes that could increase the silicon content. In steel castings, up to 1.00% of silicon is commonly present. Therefore, it may be hypothesized that the silicon was introduced during a casting process.

There are many types of casting process but the traditional method is sand casting. Sand casting is the most prevalent of all the forms of casting, which uses silica sand (SiO_2) as the mold material. This sand is inexpensive, reusable, and believed to be the source of this higher-than-normal level of silicon detected by the spectrometer. With the knowledge that the spectrometer results represent the surface properties, it would be expected that the variation in silicon would be quite high as this process is inherently difficult to control. The presence of silicon is one of the most revealing elements in the spectrometer results. The presence of the dendritic structures in the failure image (Fig. 5.7) also supports the hypothesis that the process used was sand casting. Dendritic structures are commonly formed during casting processes [25, 26].

5.5.2.4 Spectrometer analysis: Chromium content

One critical element detected by the spectrometer is chromium. Table 5.6 shows the statistical analysis results of the chromium content.

Table 5.6. One sample T-test descriptive statistics of Cr content.

$\boldsymbol{\mu}$, Mean	Standard deviation	95% CI for $\boldsymbol{\mu}$ (min)	95% CI for $\boldsymbol{\mu}$ (max)
7.980%	0.587	6.5228%	9.4372%

Firstly, students will understand expected chromium levels in common stainless steels. The minimum content of chromium in a regular stainless steel should be 10.5% [25, 26]. The spectrometer results show that the chromium content only varies from 7.49% to 8.63% with a mean of 7.980%. With this knowledge, students can eliminate stainless steel as a possible material for this tool. This is noteworthy because this inference contradicts the label on the shears as shown in Fig. 5.2.

Students will then be directed to find a possible source of the chromium content. Other than stainless steels, there are no other steel alloys that would exhibit this high-level chromium content. For example, a common steel grade that contains chromium as an alloy may have only 1% or less chromium in content [25, 26, 29].

Students will then be asked to understand the processes that would result in a high surface concentration of chromium. From here, there are a number of options that students can choose to investigate.

At first, it is possible that the manufacturer employed chromizing by chemical vapor deposition or hard chrome. However, both methods were unlikely to be chosen by the manufacturer because they are costly. Therefore, it is reasonable to assume that the manufacturer chose a more cost-effective processing method consistent with other less expensive options such as sand casting, case hardening, and plain carbon steel chosen for making this product. It is logical to assure that the manufacturer's major goal in selecting materials and manufacturing processes for the shears was minimize the manufacturing cost. Chrome plating is a low-cost chromizing process which was likely chosen by the manufacturer. In addition, hard chrome plating is expected to have a high HRC value of up to 70 [25]. Chrome plating is performed by first plating the metal with copper, then nickel, and then chromium. This also explains the presence of copper and nickel in the spectrometer results. Although nickel is commonly added to steels to increase hardenability, copper is not a common alloying element. It is possible that nickel was added as an alloying element but usually the manganese content would be higher in order to achieve a higher quality steel [25].

One obvious concern is that this hypothesis (the shears were made of a plain carbon steel instead of a stainless steel) contradicts with the label on the scissors.

Chrome plating a low carbon steel would not result in a stainless steel but would be a way for a manufacturer to mislead potential customers by making them think that they are purchasing a high-quality stainless-steel product. Product labeling is strictly controlled in many countries but not universally so. This aspect of the project allows students to explore product labeling requirements from an international perspective as well as challenge their initial assumptions made based upon the labeling.

5.6 Student Recommendations for Failure Corrective Action/ Product Improvement

Through this project, students are expected to know that statistical process control and basic statistics are powerful tools to understand the effects of a manufacturing process on the performance of final products. This understanding will allow future engineers to choose the most suitable manufacturing process and optimize the process parameters to fabricate products with desired properties. After completing above analysis, students will be required to summarize and describe the processes that were employed to manufacture the shears, their material, and the cause of failure and recommend changes to avoid such failure. This assignment will allow them to get a deeper perspective on the process-structure-property-performance relationship of the studied product.

From our results, the following conclusions can be made and potential future work can be shaped:

1. SEM imaging displays the martensitic grain structure and provides evidence of a brittle fracture mode and porosity.

a. The failure could be due to cracks originating from the surface resulting from porosity, which is known to be detrimental to the materials surface finish and ductility [25]. The porosity could be caused by entrained or dissolved gases and/or shrinkage of the solidified metal.

b. The failure could be due to discontinuities generated in the casting process such as hot tears, a common defect in castings. Hot tears occur when castings cannot shrink freely during the cooling process because of the constraints applied by the mold or core [25].

c. The brittle failure mode was confirmed by the SEM images at higher magnifications. Those images revealed more obvious signs of the brittle fracture such as more evidence of fracture developed along the cleavage planes.

2. The presence of voids and dendritic structures provide evidence that a casting process was employed in making the shears [25].
3. The large variation in the carbon content indicate that the spectrometer results only reflected the surface concentration but not the bulk properties of the material. This large variation is possibly caused by the application of a case hardening process.
4. Low levels of manganese content suggest that the material of the shears is a low carbon steel. This also supports the hypothesis that a case-hardening process was applied during the fabrication process.

5. The high levels of silicon content suggest the use of sand casting in manufacturing the shears.
6. Chromium content is too low for the material to be classified as a stainless steel and too high to represent a medium or high carbon alloy steel. The chromium must be introduced by surface treatment such as chromium plating. The application of chromium plating is further supported by the detected copper and nickel in the material.

In summary, students may deduce that the shears were made of a low carbon steel and the manufacturing process included a sand-casting process followed by case hardening and chrome plating.

Students are then required to review specifications for low carbon steels. The most common and cheapest option available is a plain carbon steel designated as AISI 1008 of ASTM A366. AISI 1008 steels only have a specification for maximum manganese content and typically will exhibit manganese levels similar to the material studied in the present project ranging from 0.30% to 0.50% [30]. Moreover, the AISI 1008 steels are cheaper than most other types of steel available on market [29]. This would align well with a manufacturing philosophy of targeting cost instead of quality. However, without further testing on the chemical composition of the bulk material, it is impossible to conclude with a high degree of confidence what the material actually is. Students may include this disclaimer in their conclusion and suggest what other types of testing is necessary to fully characterize the material.

Students can also make recommendations to improve the quality of the product. For example, sand casting mold chills may be introduced to increase the cooling rate in critical regions [26]. Students may also suggest redesigning the part geometry to decrease the stresses generated in the failure region and reduce the stress concentration.

Students may also propose different materials and processing methods for this product such as 400 series martensitic stainless steels and the application of a forging process [25]. This type of stainless steel is a common choice for cutlery due to its high hardness and corrosion resistance. Utilizing a forging process would align the grain structure of the material with the geometry of the part, which would result in optimal material properties in high stress regions. However, these changes will increase the manufacturing cost so students would need to carefully consider with a market analysis of the product. At the end of the semester, each student team will make an oral presentation about its findings to the entire class and document the project in a final report.

5.7 Conclusion

This chapter presents a PJBL case study that can be done in either a face-to-face classroom or a virtual environment. The presented educational model could be used directly in an existing course, since all the data have been provided or it could also be adapted for different contexts by replacing the existing data with a new data set.

Given results obtained from the Rockwell C hardness testing, spectrometer testing, and failure site SEM imaging, students are required to perform statistical analysis on those results to determine the material of the product, its manufacturing process, and the root cause of its failure. This PJBL case study allows the students to understand the cross-disciplinary nature of product quality as an intersection of materials science, manufacturing engineering, and engineering design. This project and the employed PJBL methodology will expose the students to material characterization techniques, manufacturing processes, statistical analysis methods, and can help them develop professional skills such as teamwork, communication, problem solving, and project management. In summary, this case study provides a pedagogical framework to bridge the gap between materials science, manufacturing, statistical analysis, and professional skills. However, this chapter does not include an analysis of student feedback to identify the students' perceptions of the presented learning activities. In the next phase, the authors will conduct qualitative research to evaluate the students' reactions employing semi-structured interviews, focus groups, as well as other assessment tools developed by Baker and Liu [23, 24]. The students will have to present their work before the class and submit a final report. The oral presentations and final reports will allow us to evaluate the course effectiveness and gauge student learning to promote student engagement and learning outcomes. A larger set of student feedback questionnaire data and student work samples will facilitate the assessment of the effectiveness of the presented educational model.

References

1. S. Ambrose, M. Lovett, M. Bridges, M. DiPietro, & M. Norman, *How Learning Works: Seven Research-Based Principles for Smart Teaching*. San Francisco, CA: Jossey-Bass, 2010.
2. V. Servant-Miklos, "Fifty years on: A retrospective on the world's first problem-based learning programme at McMaster University Medical School", *Health Professions Education*, 5(1), 2019, 3-12.

3. M. Noordin, et. al. “Problem-Based Learning (PJBL) and Project-Based Learning (PJBL) in engineering education: a comparison.” Proceedings of the IETEC’11 Conference, Kuala Lumpur, Malaysia, 2011.
4. G. Schmidt, “Foundations of problem-based learning: some explanatory notes”, *Medical Education*, 27(5), 1993, 422-432.
5. E. Graaff and A. Kolmos, “Characteristics of problem-based learning”, *International Journal of Engineering Education,* 19(5), 2003, 657-662.
6. M. Foss and Y.-C. Liu, “Creating solutions through project-based and experimental learning: A case study of the Concept Center”, *International Journal of Engineering Education*, 37(6), 2021, 1630-1642.
7. M. Foss and Y.-C. Liu, “Developing creativity through project-based learning”, Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference, virtual conference, April 15-16, 2021.
8. M. Foss and Y.-C. Liu, “Project-based learning center to bridge to students with technology”, Proceedings of 2020 Intermountain Engineering Technology and Computing (IETC), Orem, UT, USA, September 2020.
9. M. Foss, Y.-C. Liu, and S. Yarahmadian, “Project-based learning in engineering education in a virtual setting: A case study on materials and manufacturing process and applied statistics”, *International Journal of Engineering Education*, 39(5A), 2022, 1377-1388.
10. M. Foss and Y.-C. Liu, “Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center”, Proceedings of the 1st International Academy Conference on the Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.
11. M. Foss and Y.-C. Liu, “Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines”, Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.
12. Y.-C. Liu, “Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course”, *European Journal of Engineering Education*, 42(6), 2017, 800-811.
13. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers, “Theo Jansen project in engineering design course and a design example”, *European Journal of Engineering Education*, 36(2), 2011, 187-198.
14. Y.-C. Liu and Y.-Q. Dou, “Design of an industry-tied and team-oriented course for mechanical engineering seniors”, Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
15. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, “Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course”, *International Journal of Mechanical Engineering Education*, 47(4), 2019, 315-337.
16. Y.-C. Liu and F. Baker, “Development of vibration and control system through student projects”, Proceedings of ASEE SE Section Annual Conference, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
17. Y.-C. Liu, V. Meghat, and B. Machen, “Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an

engineering systems design approach", *International Journal of Design Engineering*, 8(1), 2018, 1-18.

18. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 7(2), 2017, 106-122.
19. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.
20. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
21. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
22. Y.-C. Liu, J.A. Batte, Z.H. Collins, J.N. Bateman, J. Atkins, M. Davis, D. Salley, C.L. Bethel, J.E. Ball, and C. Archibald, "Mechanical design, prototyping, and validation of a Martian robot mining system", *SAE International Journal of Passenger Car – Mechanical Systems*, 10(1), 2017, 1289-1297.
23. Y.-C. Liu and F. Baker, "A new questionnaire for assessment of a mechanical engineering senior design class", *International Journal of Mechanical Engineering Education*, 46(4), 2018, 289-301.
24. Y.-C. Liu and F. Baker, "A course assessment tool for a mechanical engineering design class", Proceedings of ASEE SE Annual Conference, Embry-Riddle Aeronautical University, Daytona Beach, FL, USA, March 4-6, 2018.
25. S. Kalpakjian and S. Schmid, *Manufacturing Engineering and Technology*, New Jersey: Pearson, 2014.
26. G. Bruce, W. Dalton, J. Neely, and R. Kibbe, *Modern Materials and Manufacturing Processes*, New Jersey: Pearson, 2004.
27. J. Reeves, E. Williams, C. Plouffe, C. Staples, W. Carlucci, R. Smith, Y. Hammi, W. Whittington, D. Dickel, Y.-C. Liu, "Combined experimental and computational failure and fatigue analysis of a socket drive adapter", *Journal of Failure Analysis and Prevention*, 21, 2021, 1434-1444.
28. M.J. Schneider and M.S. Chatterjee, "Introduction to surface hardening of steels", *ASM Handbook*, Volume 4A, *Steel Heat Treating Fundamentals and Processes*, J. Dossett and G.E. Totten, editors, ASM International, 2013.
29. E. Oberg, F. Jones, H. Horton, & H. Ryffel, (1988). *Machinery's handbook: A reference book for the mechanical engineer, designer, manufacturing engineer, draftsman, toolmaker, and machinist*. New York: Industrial Press.
30. AISI 1008 Steel, MatWeb Material Property Data, available: http://www.matweb.com/search/datasheet.aspx?MatGUID=145867c159894de286d4803a0fc0fe0f&ckck=1.

Chapter 6

Mathematical Modeling of Learning Via PJBL

Abstract

Human cognition and consciousness are perhaps the most confounding mystery. Somehow it has a linkage to the process of learning and storage of short-term and long-term memory in the form of knowledge. This chapter examines a brief background of early models in learning presented by Atkinson and Shriffrin [1] and related stochastic models utilizing probability functions. Each of these learning models capture certain facets of the learning process but are ineffective in describing the physical basis in which learning occurs. For this reason, this chapter explores analogous mathematical models based on reaction kinetics that have been shown to represent chemical reactions found in nature. Six learning models are presented of unitary, binary, reversible binary, reversible binary with mass action, and enzyme learning model reactions with and without decay. Preliminary analysis of time series plots, phase line diagrams, and phase plane plots were conducted to illustrate equilibrium conditions and stability of the models. Each model is examined in terms of its limitations in the philosophy and inability to capture certain elements that are understood about the learning process. Finally, this chapter concludes that the feasibility of understanding behavior such as stability through the tools of applied mathematics and thereby illuminating certain layers of human cognition and learning is a useful tool in examining the suitability of a possible deterministic model that could describe the learning process. Further analysis with empirical data would validate the suitability of the presented models.

6.1 Introduction

Of the many mysteries that remain, human cognition and consciousness is perhaps the most confounding one. Both are inextricably tied to a vast array of knowledge that is present in an individual. This knowledge, accumulated over the life of the individual, shapes her/his perception. In both professional and personal lives, decisions are based upon information at hand combined with past learning. In fact, every single advancement throughout the human history is largely a result of building upon the learning and discoveries that have been made by others.

The objective of every educational institution is to transfer knowledge and information to students through the process of learning so that the acquired knowledge can be translated into decisions, skills, and actions as they enter the workplace. As such, learning as a process is of utmost importance but is largely not well understood. It has easily been established that learning requires concentration, time, focused intellectual work, as well as mental wellbeing. Numerous mathematical models have been created that attempt to capture the learning process as well as the simultaneous process of forgetting [1]. The aim of this chapter is to examine the feasibility of learning models developed based on reaction kinetics using applied mathematics tools. Describing learning as a reaction does mimic the experience of the learner when achieving an "Aha" moment in understanding and offers a potential philosophical explanation for many of various variables that are understood to influence learning such as time, quality of instruction, motivation, genetics, and background knowledge. By representing learning as a process like a chemical reaction, an appropriate model could be used to justify incorporating problem-based learning into teaching curriculum by establishing that this learning strategy can function to increase long-term learning and thereby decrease the rate of memory loss.

6.2 Background

6.2.1 The Atkinson-Shiffrin Theory

The Atkinson-Shiffrin (AS) theory of human memory is a relevant concept to learning. Developed in 1968, it came about in a period that is considered the 'cognitive revolution' due to the tremendous amount of research being performed in experimental psychology [2, 3]. At the same time, there was a simultaneous interest in describing these findings related to learning and memory with the elegance of mathematical modeling. The premise of this learning model is related to the storage of knowledge in the form of memory. In essence, learning is only effective if the knowledge gained can be retained. AS theory provides a model of learning based upon three memory blocks: sensory registry (SR), short-term memory (STM), and long-term memory (LTM). This theory presents an information processing model similar to a computer with inputs, outputs and processes in between. Initially, sensory organs detect information which later enters the sensory memory. If the information is deemed noteworthy, it can enter short term memory and then be transferred to the long-term memory if the information is repeated. If repetition does not occur, the information is forgotten. Even though this model has obvious limitations, namely, it is possible to create long-term memory without repetition, it served as a starting point to build upon to develop and refine mathematical models to describe the learning process as it applies to an academic setting. It is a logical conclusion to prioritize learning to achieve long-term memory and thereby prepare students for their careers with a strong and wide foundation [3].

There have been several mathematical models that have been developed by researchers in psychology, science teaching, mathematics, and others with the goal of representing the learning process. However, those models are empirical models that were developed by fitting input variables to numerical results; therefore, they fail to explain physiological process that occurs when an individual learns. An advanced numerical model that can represent the biochemical process is greatly needed to better understand and quantify how a unique individual learns. Shikaa and Ajai built upon a logistical model first presented by the AS theory by introducing the Hicklin's concept of dynamic equilibrium theory to represent the concept of mastery learning [4,5]. Bush and Mosteller proposed learning as a combination of a myriad of factors related to probability [6] while Anderson recognized that there was a rate-based element of a potential learning model [7]. Many of these models of learning in turn motivated a response in criticism to the logic in the development [8-10] highlighting the difficulty in describing the learning process effectively. However, although an accurate model to describe learning is heretofore nonexistent, many researchers are still motivated that it is possible to develop one and have done so by building upon the concept of learning as a probability and relating it to biological processes or plateau phenomena [11-13]

Fredrick and Walberg presented a review of measures of instructional time as a predictor of outcomes to illustrate the importance of learning as a function of time in the theory of educational productivity [14]; while Aldridge presented a model of learning as a linear combination of independent variables [15] using regression techniques and data based on the belief that students' performance is normally distributed. Aldridge's model was revised until it reached a form of a logistical model that is inherently stochastic. An empirical study that further inspected Aldridge's model attested that Aldridge's model has strengths and weaknesses common to many of the previous models. All these models contain some elements of learning but none of them can completely capture the multi-dimensional process of learning due to a lack of understanding of the biochemical process of learning. They also rely heavily upon empirical data for calibration rather than constants that are inherently deterministic [16].

6.2.2 Reaction Kinetics

Mathematical models of reaction kinetics are a powerful mathematical application involving differential equations that describe the basis of chemical kinetics as well as virus pathways and epidemics. Taking to heart the cliché that 'life is chemistry,' it is relevant to examine if the mechanisms that describe molecular biology and biochemical kinetics through processes such as enzyme kinetics or nerve signal propagation are analogous to the process of learning [17]. Because reaction kinetics models have been successfully developed to describe several incredibly important natural phenomena, the theory of reaction kinetics is a logical approach to describe yet another natural phenomenon, learning.

6.2.3 Project-Based Learning (PJBL)

PJBL was developed in 1965 by 5 faculty of Health Sciences doctors led by founding Dean John Evans of McMaster University [18]. It is a learning approach in which students solve problems in small groups under the supervision of a tutor [18]. The PJBL process is driven by the student, facilitated by the tutor, and is based on an educational approach where the learning is driven by problems or can be thought of as "learning through application". In this approach, learners (students) are encouraged to pursue knowledge by asking questions. PJBL has been regarded as a key strategy for creating independent thinkers and learners in the medical education community [18-20].

Following the implementation of PJBL in the education of medicine, it has since been expanded to other fields and is considered a solution to some of the issues facing today's education [20]. For example, faculty at Weber State University established a PJBL center to achieve a double mission of being an active community member and providing opportunities for engineering students to gain needed skills in problem solving and project management [21-26]. It has been found that the PJBL learning approaches greatly facilitated the training in competencies related to interpersonal skills and technical aptitude, experience of solving real-world problems from an engineering perspective, and collaborative learning [27-29]. Liu and coworkers successfully integrated the PJBL mode in his senior mechanical engineering classes by introducing more than 20 projects from industry sponsors, university research centers, and a state agency [27, 29-31]. It was found from Liu's practice that the implementation of PJBL in course curricula struck the balance between achieving desired student learning outcomes and creating opportunities for enriching the student's educational experience [31-37]. As such, by examining the success of PJBL, there is evidence that learning model presented by AS has an aspect of application in addition to sensory registry.

6.3 Learning Models Based Upon Reaction Kinetics

6.3.1 Learning as Unitary Reaction (LUR)

The simplest learning model is a unitary reaction model in which a person is exposed to information, X, and then after a certain time, some amount of learning has occurred where knowledge now exists in the individual as shown in Eqn. (6.1).

$$X \rightarrow \text{Knowledge} \tag{6.1}$$

Utilizing concepts in reaction kinetics, the rate of learning is proportional to the amount of information presented, or r = kX where k is the learning constant for the individual. This means that information is ‘consumed’ by the individual at the rate of $-kX$, as shown in Eqn. (6.2).

$$\frac{dX}{dt} = -kX \tag{6.2}$$

Here the “–” indicates that the information is consumed in a learning reaction.

A function for information consumption that directly leads to knowledge can be solved from Eqn. (6.2) as a first order ordinary differential equation shown in equation 6.3 where X_o represents the initial conditions of knowledge and k represents the rate constant of information consumption.

$$X(t) = X_o\, e^{-kt} \tag{6.3}$$

This function is useful to establish a simple learning models where memory is perfect and all information that is presented is converted into knowledge. The LUR model also offers some expected results such as the form of an exponential function which indicates the rate at which learning occurs is not constant. With an examination of an exponential function, it can be concluded that the transfer of information into knowledge happens faster in the early stages of learning and slows down as time passes. This is in contrast to some research that shows a linear relationship between knowledge gained through learning and time [14], but could be explained with the appropriate time scale. For example, an exponential function of time can be approximated as linear when the change in time becomes close to zero. The model of LUR is illustrated in Fig. 6.1, in which the information is consumed as a negative exponential function of time and acquired knowledge is increased as a positive exponential function of the time.

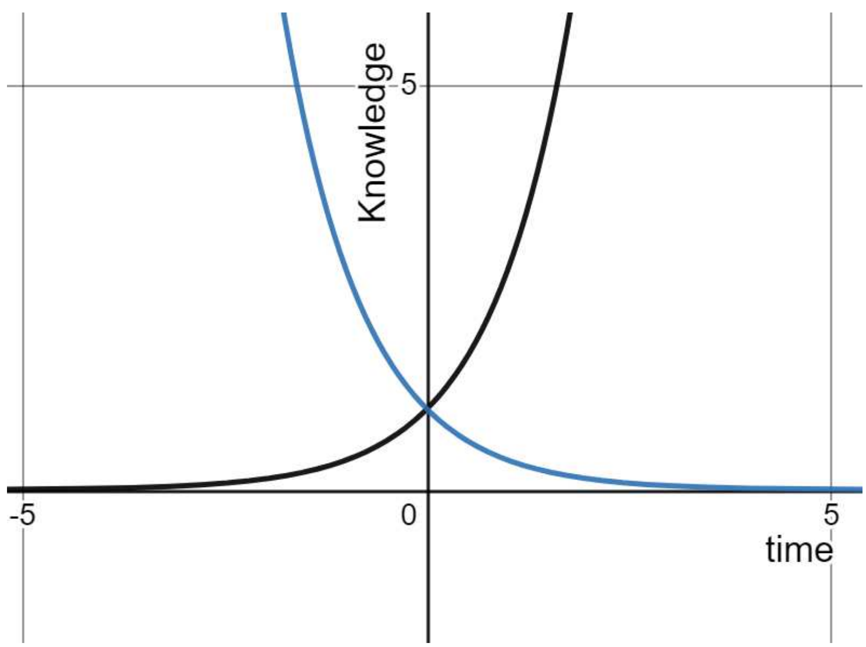

Figure 6.1. Learning as Unitary Reaction time series plot

It should also be noted that the rate constant in many chemical reactions is not in fact constant and is instead a function of a number of variables. In the case of an individual's learning, the rate constant shown as *k* in the model could be understood as the Arrhenius rate constant shown in Eqn. (6.4).

$$k = Ae^{-\frac{E_a}{RT}} \tag{6.4}$$

Where A is the temperature independent pre-exponential factor, E_a is the activation energy for the reaction, R is the universal gas constant and T is the absolute temperature. By incorporating the Arrhenius rate constant into the LUR model, equation 6.5 is created.

$$\mathrm{X(t)} = \mathrm{X}_o \mathrm{e}^{-Ae^{-\frac{E_a}{RT}}\mathrm{t}} \tag{6.5}$$

By expanding the LUR with the Arrhenius rate constant, certain elements that are understood about learning could be captured. The rate of learning is a function of quantities such as motivation which might include incentive or disincentive as well as an individual's capacity to learn coupled with their background knowledge and the quality of the learning environment. While likely a learning constant would include different variable than the Arrhenius rate constant, there may be an analogous form that is similar.

While this model is simple and easy to understand, it overlooks several significant features in a learning process. This model assumes that all information presented is consumed at the same rate and translated into knowledge and the reactions happens until all information is consumed. For example, a student may learn one topic at a different rate than another. The LUR model also neglects the memory loss, the counterpart of a reversible reaction in a chemical reaction. As such, the unitary reaction model must be expanded to consider learning as a binary reaction.

6.3.2 Learning as Binary Reaction (LBR)

In a binary chemical reaction, two different molecules combine to form a new product (Eqn. (6.6)):

$$X + Y \rightarrow Z \tag{6.6}$$

Taking advantage of the AS theory, Eqn. (6.6) can be modified as a binary learning reaction model where Z is the gained knowledge; X represents the information that is gained through the senses and would include everything acquired from listening to a lecture to reading a text book or watching a video; and Y represents the interaction of the learner with the information and would include everything from solving a problem to completing a project following the PJBL methodology. The LBR model by nature, remains flawed because the model presumes that no knowledge can be gained from sensing alone and application of that information (practice) is necessary to be converted into knowledge. This is clearly not the case; however, this model likely does apply to certain fields. For example, in the practice of medicine, one may read volumes of books on surgery and observe others performing surgeries but likely will find that the extent of their knowledge gained from these sensing methods is insufficient to the practice of performing a surgery. For the quantity of knowledge to reach levels of mastery where one can become a professional surgeon, extensive application (practice) is necessary.

By applying the law of mass action, it can be established that the rate of the reaction, or learning, is proportional to the product of the two reactants X and Y and the rate constant *k* shown in Eqn. (6.7) [17]:

$$r = kXY \tag{6.7}$$

The differential equations can be written by the following shown in Eqn. (6.8).

$$\frac{dX}{dt} = -\mathrm{r} \quad \frac{dY}{dt} = -\mathrm{r} \quad \frac{dZ}{dt} = -\mathrm{r} \tag{6.8}$$

From here, several conservation laws can be developed shown in Eqn. (6.9).

$$\frac{dX}{dt} - \frac{dY}{dt} = 0 \qquad \frac{dX}{dt} + \frac{dZ}{dt} = 0 \quad \frac{dY}{dt} + \frac{dZ}{dt} = 0 \tag{6.9}$$

Which follows that $X - Y = $ Constant, c, which can be used to rewrite the differential equations with one unknown in Eqn. (6.10) and (6.11).

$$\frac{dX}{dt} = -\,k\mathrm{XY} = -\,k\mathrm{X}(\mathrm{X}\text{-}c) \tag{6.10}$$

$$\frac{dZ}{dt} = k\mathrm{XY} = k\mathrm{X}(\mathrm{X} - c) \tag{6.11}$$

Which can be rewritten in the form of Eqn. (6.12) to resemble a logistic model which is consistent with many of the prior mathematical models on learning that have been presented.

$$\frac{dX}{dt} = kcX(1 - \frac{X}{c}) \quad (6.12)$$

where and c is the learning capacity of an individual and the term kc can be represented as the intrinsic learning rate. Using Eqn. (6.12) to solve for dX/dt = 0, the stability of the model can be seen in the generic phase line plot Fig. 6.2. The condition of zero information is unstable and the condition when the information is equal to the learning capacity (dX/dt = 0) is stable.

The LBR model offers some advantages over the LUR model as this model resembles a logistic function. In the LBR model, the constant c represents the 'carrying capacity' or plateau phenomena that can be used to describe learning as a function that represents diminishing returns with time as has been demonstrated by other presented models [11-13].

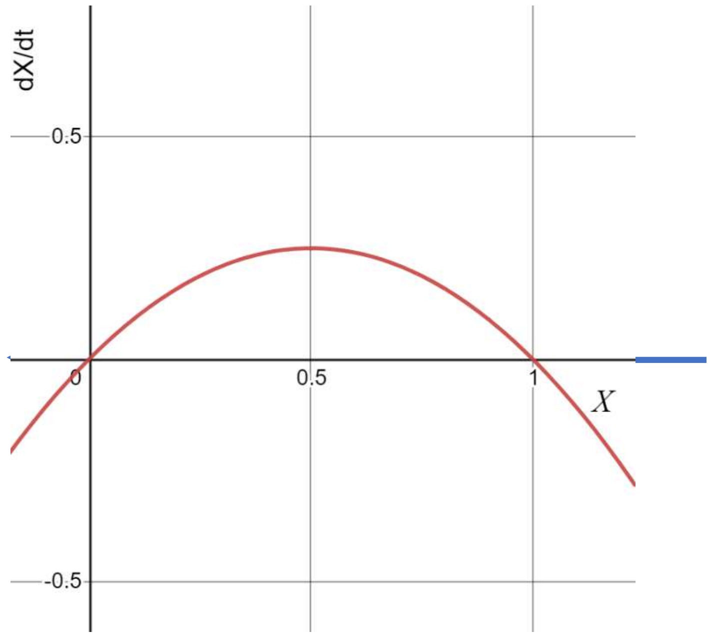

Figure 6.2. Generic phase line plot of binary learning for $\frac{dX}{dt}$

There are, however, obvious limitations to the application of the LBR model. Just like the LUR model, it does not include a mechanism to capture the memory loss. It should also be noted that this model assumes a perfect translation of information into knowledge without any errors in conceptual understanding, which is counter to intuitive understanding of the learning process. While it does capture more that is understood about learning than the LUR model by including plateau phenomena, it needs to include a mechanism of memory loss through forgetting that can be captured as a reversible reaction.

6.3.3 Learning as Reversible Binary Reaction (LRBR)

One possible way to capture the memory loss associated with learning is to consider a reversible binary reaction. Using the chemistry analogy, an initial reaction of constituents X and Y forms the product Z with the rate constant k_1 as shown in Eqn. (6.13). The product, is broken down into its reactant constituents by a reversible reaction with rate constant k_{-1} as shown in Eqn. (6.14). Utilizing the law of mass action, the rate of reaction is proportional to the product of the reactant concentrations as shown by Logan [17] thereby allowing for an expression of r_1 and r_{-1} as shown in Eqns. (6.13, 6.14). Undoubtedly, this is not the real mechanism of the loss of knowledge but it is viable to use this mechanism to model the process of knowledge loss. In the LRBR model, a term k_{-1} is introduced, which represents the loss of knowledge or rate constant for the reversible reaction and would only be considered as a constant under certain situations. For example, if an individual is well-rested and able to focus on the information it could be expected that this constant would be comparatively smaller than if the individual is attempting to multi-task or 'cramming' in the wee hours of the evening.

$$X + Y \overset{k_1}{\rightarrow} Z \qquad r_1 = k_1 XY \tag{6.13}$$

$$Z \underset{k_{-1}}{\longrightarrow} X + Y \quad r_{-1} = k_{-1} Z \tag{6.14}$$

With this model, the rate equations are shown in Eqn. 6.15 by utilizing the property that rates add for a system of reactions [17].

$$\frac{dX}{dt} = -r_1 + r_{-1}\,, \quad \frac{dY}{dt} = -r_1 + r_{-1}, \quad \frac{dZ}{dt} = r_1 - r_{-1} \tag{6.15}$$

From which the following conservation laws can be determined as shown in Eqn. 6.16.

$$\frac{dX}{dt} - \frac{dY}{dt} = 0 \tag{6.16}$$

Solving the differential equation shown in Eqn. (6.16) follows that $X - Y =$ constant $= c$, an expression called a conservation law [17] is created. Eqn. (6.17) is the conservation laws for the remaining terms.

$$X - Y = c_1, \quad X + Z = c_2, \quad Y + Z = c_3 \tag{6.17}$$

These constants add new dimensions of learning because they are based upon initial conditions shown in Eqn. (6.18) at time t = 0. These initial conditions can be used to represent the background knowledge of an individual and the level of understanding that is present in foundational topics. They also can function as a way of capturing the attitude of the learner and the learner's preferences, strengths and weaknesses in learning new things. These psychological factors are complicated and numerous but would build into a framework that could be captured with initial conditions. For example, one qualitative factor that contributes to student success is the feeling of belonging. If, for example, a student feels that they do not belong in the field of study, this could influence their ability to learn the information presented and translate it into knowledge [38-42]. The combination of the constants derived from initial condition and rate constants is an innovative way of addressing the nature versus nurture dilemma in human behavior and development. Clearly there is a genetic component of learning captured by the *k* constants and an environmental or cultural component captured by the *c* constants.

$$X(0) = X_0 \quad Y(0) = Y_0 \quad Z(0) = Z_0 \tag{6.18}$$

The constants can be determined from the initial conditions shown in Eqn. (6.19).

$$X - Y = c_1 = X(0) - Y(0) \tag{6.19}$$

The above conservation laws shown in Eqn. (6.17) can be used to derive a differential equation for X and Z from Eqn. (6.15):

$$\frac{dX}{dt} = -k_1XY + k_{-1}Z = -k_1X(X-c_1) + k_{-1}(c_2 - X) \tag{6.20}$$

$$\frac{dZ}{dt} = k_1XY - k_{-1}Z = -k_1(c_2 - Z)(c_3 - Z) + k_{-1}Z \tag{6.21}$$

Analysis of Eqns. (6.20) and (6.21) have been done that illustrate the behavior of the LRBR model as shown in the generic phase line diagrams in Figs. 6.3-6.5. Figs. 6.3 and 6.4 show the phase line diagrams and stability for $\frac{dX}{dt}$ and $\frac{dZ}{dt}$ with positive c constants and Fig. 6.5 shows $\frac{dZ}{dt}$ with negative c constants. Figs. 6.4 and 6.5 can be used to understand how individuals with the same genetic makeup including capacity to learn and rate of learning could achieve knowledge in very different ways depending upon their initial conditions.

Like the LBR model, as illustrated in Figs. 6.3 and 6.4, two equilibrium conditions exist in the LRBR model (Eqn. (6.20 and 6.21)). Of particular note is a stability condition in which the information content is equal to the capacity of the individual. It also can be observed that the conditions where the change in knowledge is positive or negative, implying a theoretical ability to optimize the rate of change of knowledge.

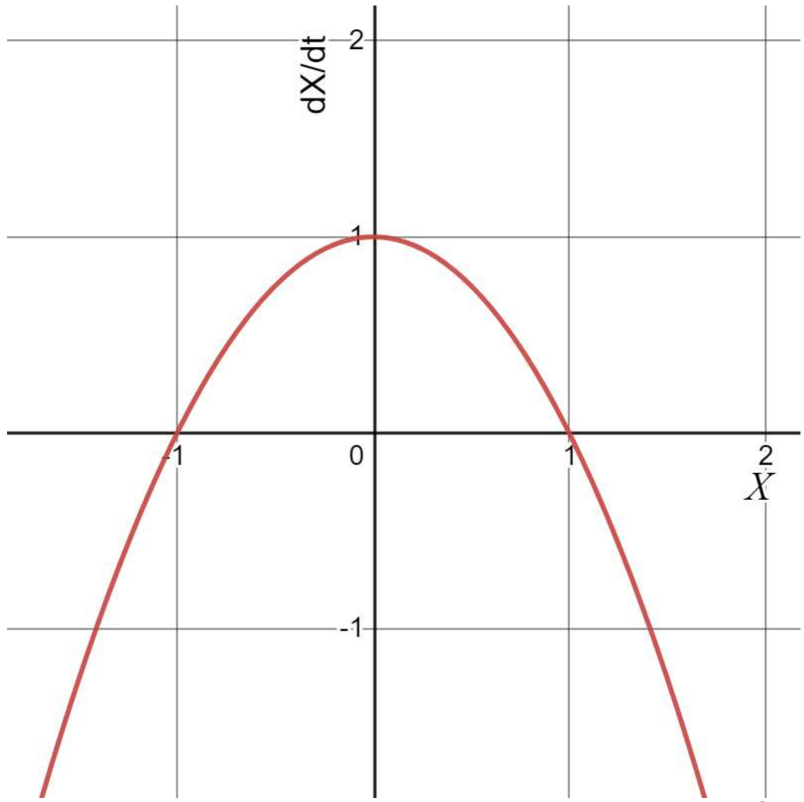

Figure 6.3. Generic phase line diagram of reversible binary learning for $\frac{dX}{dt}$ with positive c constants.

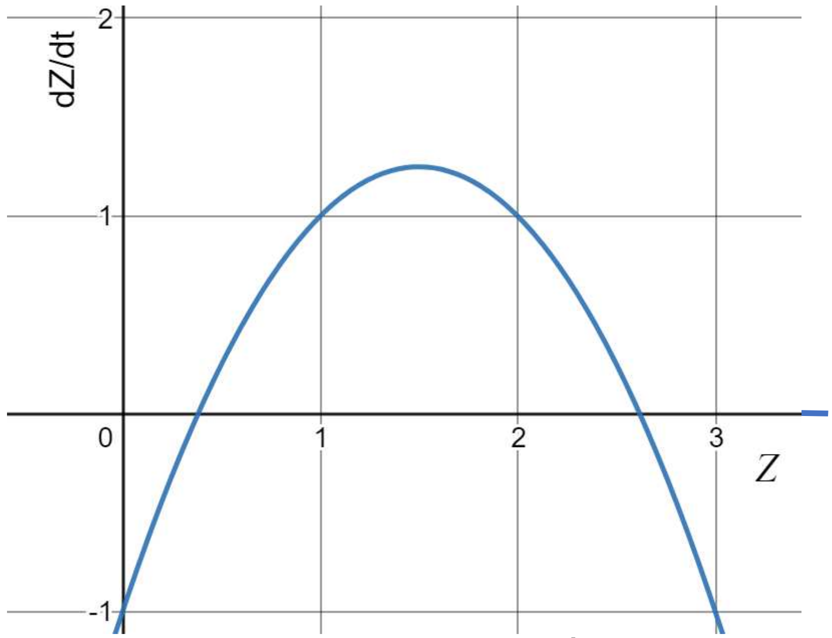

Figure 6.4. Generic phase line diagram of LRBR for $\frac{dZ}{dt}$ with positive c constants.

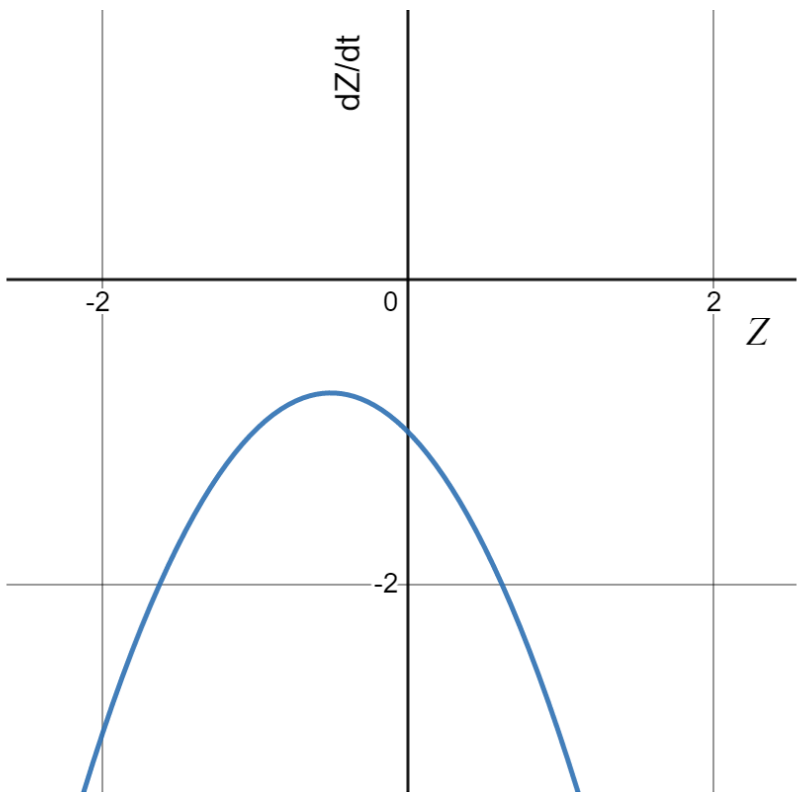

Figure 6.5. Generic phase line diagram of LRBR for $\frac{dZ}{dt}$ with negative c constants.

It is also of interest to examine the equilibrium conditions of this model. At equilibrium or $\frac{dZ}{dt} = 0$, an individual would not be retaining any knowledge from their efforts in learning. There are likely many students throughout history that have experienced equilibrium conditions in their attempt to learn new knowledge. When the differential equation $\frac{dX}{dt}$, Eqn. (6.20) is equal to zero Eqn. (6.22) is given.

$$k_1XY = k_{-1}Z \tag{6.22}$$

There are still several limitations that remain in this model and analysis. Namely, this model does not provide a way to identify short-term versus long-term knowledge. Also, this model cannot distinguish different methods of presenting the information; nor is the model able to differentiate effectiveness of differing methods of teaching. Thus, the LRBR model needs to be further improved to address these shortcomings.

6.3.4 Learning as Reversible Binary Mass Action Reaction (LMAR)

Building upon the limitations of the LRBR model, it is possible to continue with the reaction kinetics theory to model knowledge loss through the unintentional act of forgetting as well as the formation of both short-term and long-term memory where the knowledge is stored. These two 'reactants' form the reversible reaction where both short-term and long-term knowledge are represented by W and Z, respectively (Eqn. (6.23)).

$$mX + nY \rightleftarrows pW + qZ \qquad \text{with } k_1 \text{ and } k_{-1} \tag{6.23}$$

In above equation, m, n, p, and q are coefficients for each term, in which m and n are related to the quantity of the stimulus of information and p and q denote a theoretical quantity of short term and long term knowledge that has been gained by the rate and reversible reaction constants k_1 and k_{-1}. Utilizing the law of mass action, the rate of reaction is proportional to X^mY^n [17], the following rates can be defined as shown in Eqn. (6.24):

$$r_1 = k_1 X^m Y^n, \quad r_{-1} = k_{-1} W^p Z^q \tag{6.24}$$

From Eqn. (6.23), the rate equations are developed for each component, $X, Y, W,$ and Z.

$$\frac{dX}{dt} = -\mathrm{r}1 + \mathrm{r}-1 \quad \frac{dY}{dt} = -\mathrm{r}1 + \mathrm{r}-1 \frac{dW}{dt} = \mathrm{r}1 - \mathrm{r}-1 \quad \frac{dZ}{dt} = \mathrm{r}1 - \mathrm{r}-1 \tag{6.25}$$

The following differential equations (Eqns. (6.27-6.29) can then be obtained by substituting Eqn. (6.26) into Eqn. (6.25) giving the following conservation laws where c_is represent constants from initial conditions:

$$X - Y = c_1 \qquad X + Z = c_2 \qquad Y + Z = c_3 \qquad W - Z = c_4 \qquad X + W = c_5 \qquad Y + W = c \tag{6.26}$$

The differential equations then are obtained as shown in Eqn. (6.27-6.29):

$$\frac{dX}{dt} = -\,k_1X^mY^n + k_{-1}W^pZ^q = -\,k_1X^m(X - c_1)^n + k_{-1}(c_5 - X)^p(c_2 - X)^q \quad (6.27)$$

$$\frac{dW}{dt} = k_1X^mY^n - k_{-1}W^pZ^q = -\,k_1(c_5 - W)^m(c_6 - W)^n - k_{-1}W^p(W - c_4)^q \quad (6.28)$$

$$\frac{dZ}{dt} = k_1X^mY^n - k_{-1}W^pZ^q = k_1(c_2 - Z)^m(c_3 - Z)^n - k_{-1}(c_4 + Z)^pZ^q \quad (6.29)$$

A generic phase diagram (Fig. 6.6) was created to better understand the behavior of the LMAR model with positive c constants and negative c constants (Fig. 6.7). In this model, it is assumed at all constants are equal to 1 and all exponents are 2. As can be seen in Fig. 6.6, this model presents one equilibrium condition that is stable. It also shows a very narrow range where the change of knowledge, $\frac{dZ}{dt}$, is positive and the total knowledge, Z is positive. Figure 6.7 presents one equilibrium condition that is unstable.

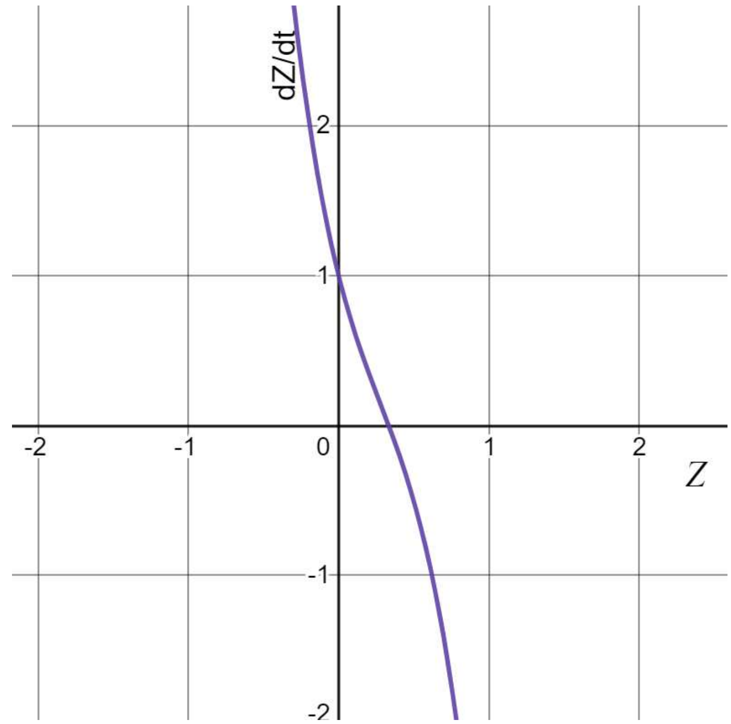

Figure 6.6. A generic phase line diagram of $\frac{dZ}{dt}$ for LMAR model with positive c constants.

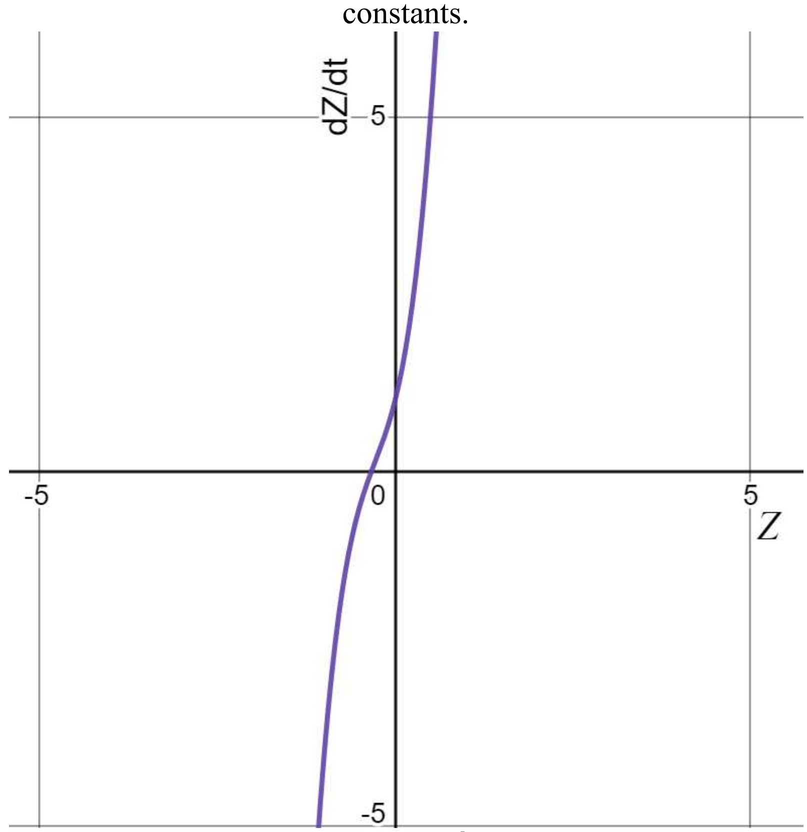

Figure 6.7. A generic phase line diagram of $\frac{dZ}{dt}$ for LMAR model with negative c constants

There exist several flaws in the philosophy of this model. Firstly, this model presumes that the short-term and long-term knowledge are gained concurrently, which violates the AS theory. The model also includes many constants, whose values are very difficult to be calibrated from empirical data.

6.3.5 Learning as Enzyme Kinetic Reaction Model (LEKR).

In an enzyme kinetic model, an intermediate complex is created before the product is formed [17]. This can be a useful analogous model to capture the change from information to the short-term memory represented by the variable W and transfer it through another process into the long-term memory represented by the variable Z. In this model, we assume that X represents the information that is to be consumed and Y represents the interaction with that information through an interaction like PJBL. In a typical reaction of a metabolic pathway catalyzed by an enzyme, the final product is produced and the enzyme is recovered [17]. In the LEKR model, it makes more sense to model the catalyst, Y, as a consumable rather than recovered as shown in Eqn. (6.30).

$$mX + nY \rightleftarrows pW \rightarrow qZ \tag{6.30}$$

Giving the following rates and rate equations shown in Eqn. (6.31, 6.32) from the law of mass action [17].

$$r_1 = k_1 X^m Y^n, \;\; r_{-1} = k_{-1} W^p, \;\; r_2 = k_2 W^p \tag{6.31}$$

$$\frac{dX}{dt} = -r_1 + r_{-1} \qquad \frac{dY}{dt} = -r_1 + r_{-1} \quad \frac{dW}{dt} = r_1 - r_{-1} - r_2 \quad \frac{dZ}{dt} = r_2 \tag{6.32}$$

Giving the following conservation laws shown in Eqn. (6.33):

$$X - Y = c_1 \qquad X + W + Z = c_2 \qquad Y + W + Z = c_3 \tag{6.33}$$

The differential equations become:

$$\frac{dX}{dt} = -k_1 X^m Y^n + k_{-1} W^p = -k_1 X^m (X - c_1)^n + k_{-1} W^p \tag{6.34}$$

$$\frac{dW}{dt} = k_1 X^m Y^n - k_{-1} W^p - k_2 W^p = k_1 X^m (X - c_1)^n - k_{-1} W^p - k_2 W^p \tag{6.35}$$

$$\frac{dZ}{dt} = k_2 W^p \tag{6.36}$$

The nonlinear systems of Eqns. (6.34-6.36) can be examined further with phase plane plots. For simplicity, generic phase plane plots are created assuming all exponents, (m, n, p) are unitary values equal to 1 as well as constants, c_i. While this assumption does eliminate many of the complexities of a learning model that can capture not only the qualities of the instruction and genetic ability of the individual, the simplification does allow for the evaluation of stability through phase plane plots and as a result does illuminate certain elements of the learning process. Figs. 6.8, 6.9, and 6.10 illustrate the relationship between X and W, W and Z, and X and Z respectively.

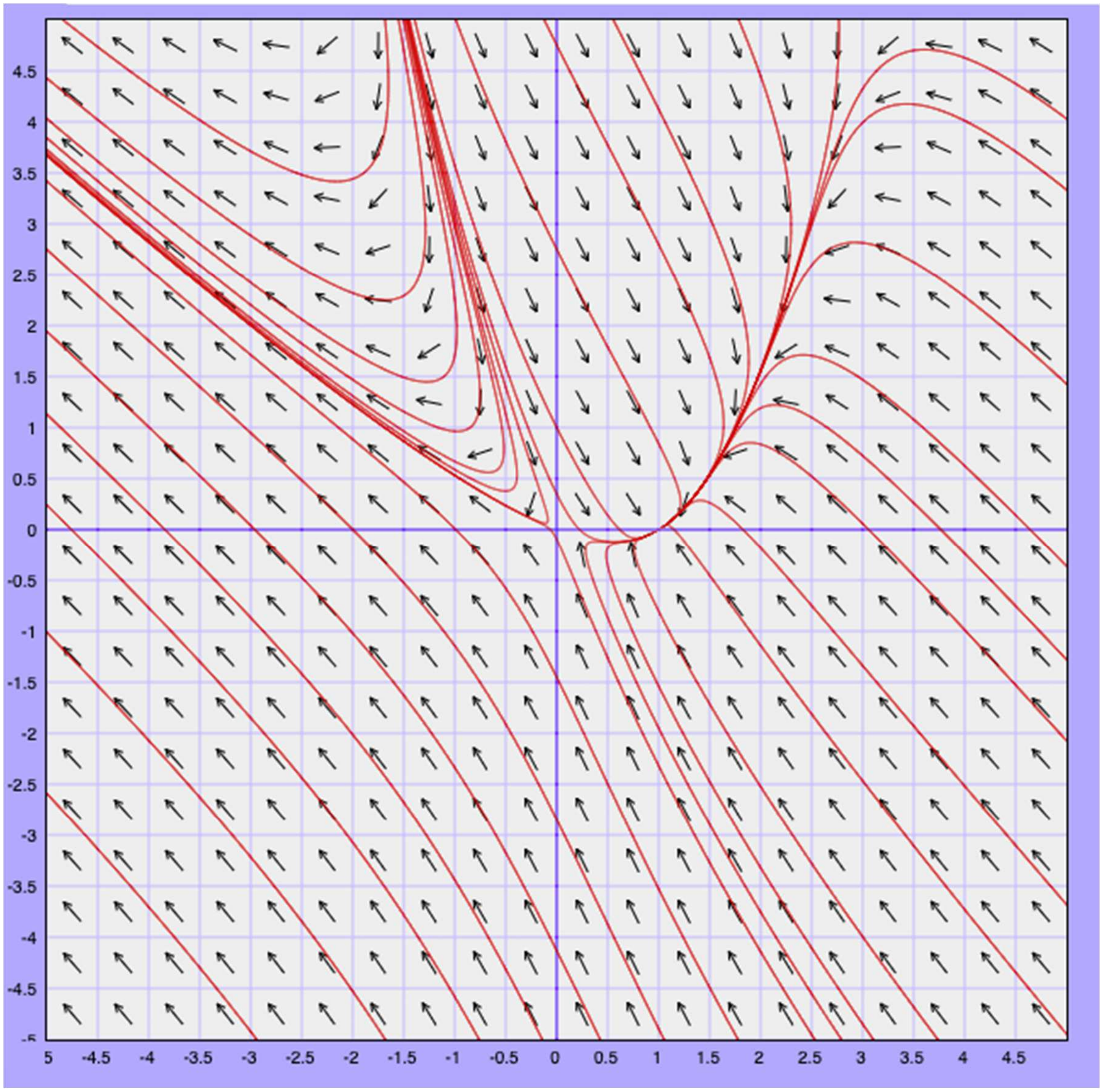

Figure 6.8. Generic phase plane plot of X and W based on the LEKR model

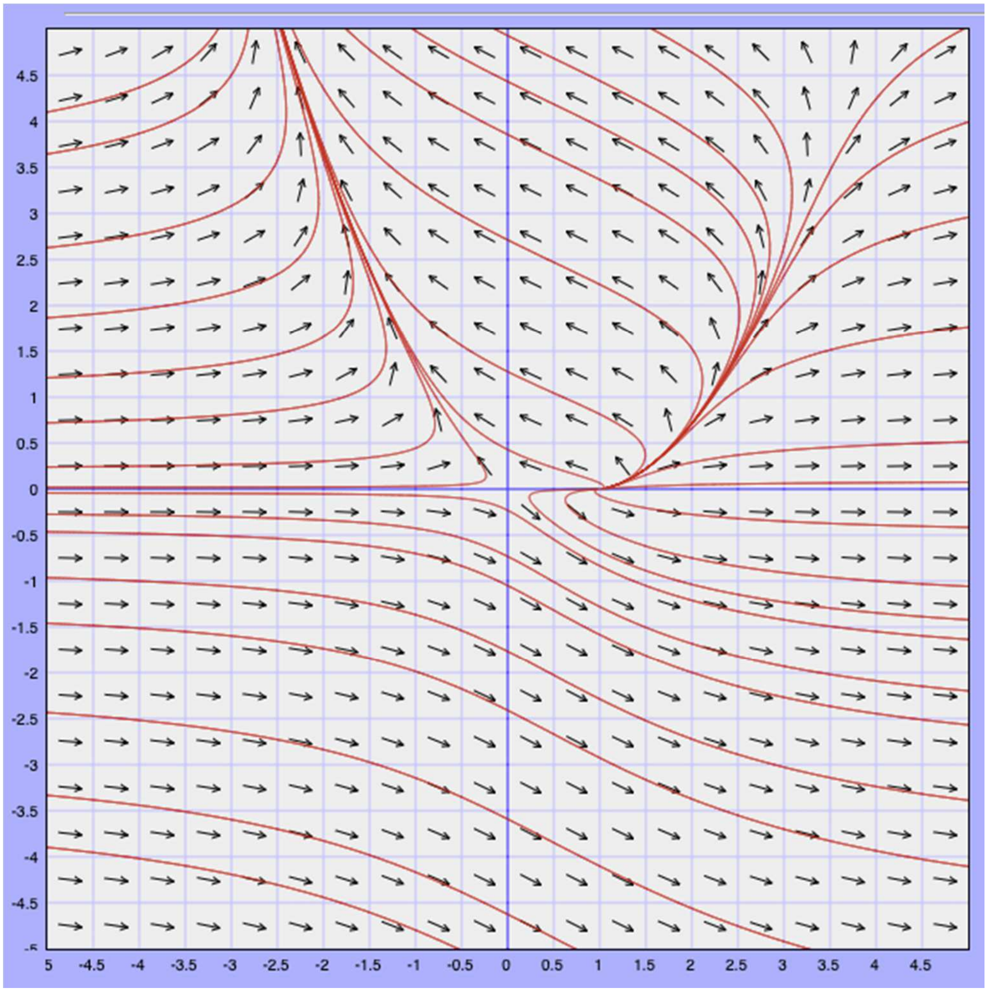

Figure 6.9. Generic phase plane plot of W and Z based on the LEKR model

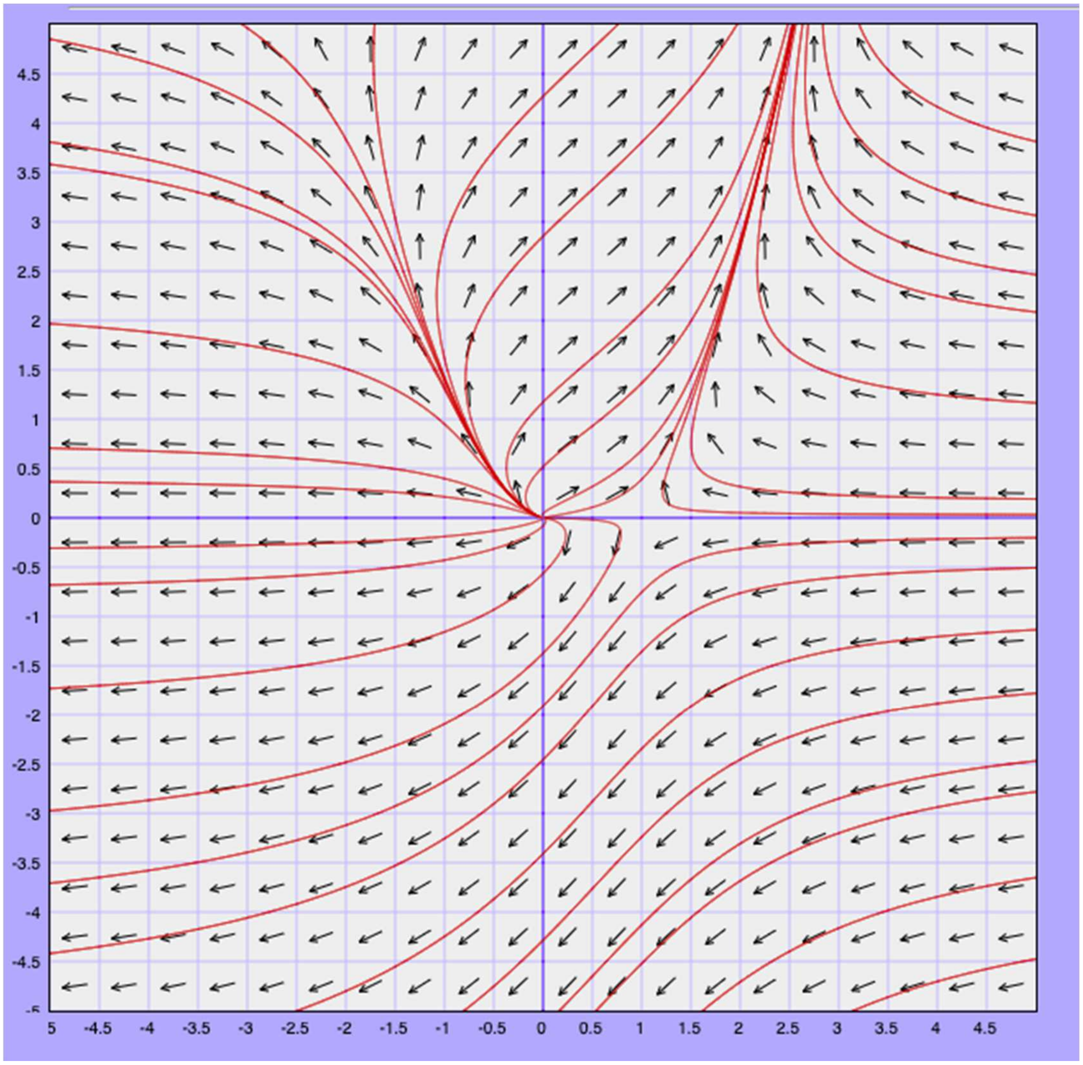

Figure 6.10. Generic phase plane plot of X and Z based on the LEKR model

The most interesting observation that are offered by Figures 6.8-6.10 is an examination of stability. When graphing parametric equations on the phase plane such as those in Eqn. (6.34-6.36), the equilibrium or steady state condition is represented by a critical point. By examining these diagrams from the basis of the Poincaré-Bendixson theorem, stability can also be observed which represents a degree of permanence in an equilibrium solution. A critical point is stable if all paths that are nearby remain near the point for all time $t > 0$ [17]. Fig. 6.8 indicates a stable node between the sensory information, X and the short-term memory, W; however, there are no stability points between any functions of Z, or the long-term memory. This would be supported by a hypothesis that forgetting is a constant process and that no knowledge can be retained indefinitely. However, this concept would be refuted when examined alongside research in the genetic component of trauma as some recent studies have suggested traumatic experiences can alter genes and be passed down [43]. This research would support a model that does demonstrate stability as it would indicate that some learning can occur on a genetic level that is beyond the time scale of the individual. This might imply that there is some stability in the long-term memory, Z counter to this model.

Of course, this model still has its own limitations. For example, there is no process in this model that describes the decay of long-term memory nor is there a process in which the short-term memory is bypassed and the long-term memory is formed initially, both of which should be represented in a learning model. However, as each of the models discussed in this chapter build in complexity, certain elements that align with observations of the learning process are developed and captured.

6.3.6 Learning as Enzyme Kinetic Reaction with Decay Model (LED)

Improving upon the model presented in 6.3.5, a process to represent the decay of long-term knowledge is introduced in the learning as enzyme kinetic reaction with decay (LED) model. The process of decay, or reduction in the term, Z, represents long-term memory loss and is a necessary component to include in a learning model. Similar to the LEKR model, short-term memory is represented by the variable W and transfers through another process into the long-term memory represented by the variable Z. In this model, we assume that X represents the information that is to be consumed and Y represents the interaction with that information through an interaction like PJBL. In a typical reaction of a metabolic pathway catalyzed by an enzyme, the final product is produced and the enzyme is recovered [17] and the decay process generates the terms mX and nY. These terms, are not intended to be quantifiable or measurable but rather are defined by the rate of the increase or decrease in short term or long term knowledge. It is reasonable to presume that information is neither created nor destroyed nor consumed in the process of learning. The variables m, n, p, q, and r represent a theoretical constant that could be used to customize the model to genetic and environmental effects. The LED model is shown in Eqn. (6.36).

$$mX + nY \rightleftarrows pW \rightarrow qZ \rightarrow mX + nY \qquad (6.36)$$

Giving the following rates and rate equations shown in Eqn. (6.37, 6.38) from the law of mass action [17].

$$r_1 = k_1 X^m Y^n \; r_{-1} = k_{-1} W^p \; r_2 = k_2 W^p \; r_3 = k_3 Z^q \qquad (6.37)$$

$$\frac{dX}{dt} = -r_1 + r_{-1} + r_3 \quad \frac{dY}{dt} = -r_1 + r_{-1} + r_3 \quad \frac{dW}{dt} = r_1 - r_{-1} - r_2 \quad \frac{dZ}{dt} = r_2 - r_3 \qquad (6.38)$$

Giving the following conservation laws shown in Eqn. (6.39) which interestingly mimic the conservation laws in Eqn. (6.33):

$$X - Y = c_1 \quad X + W + Z = c_2 \quad Y + W + Z = c_3 \qquad (6.39)$$

The differential equations become:

$$\frac{dX}{dt} = -k_1X^mY^n + k_{-1}W^p + k_3Z^q = -k_1X^m(X - c_1)^n + k_{-1}W^p + k_3(c_2 - X - W)^q = -k_1X^m(X - c_1)^n + k_{-1}(c_2 - X - Z)^p + k_3Z^q \tag{6.40}$$

$$\frac{dW}{dt} = k_1X^mY^n - k_{-1}W^p - k_2W^p = k_1X^m(X - c_1)^n - k_{-1}W^p - k_2W^p = k_1(c_2 - W - Z)^m(c_3 - W - Z)^n - k_{-1}W^p - k_2W^p \tag{6.41}$$

$$\frac{dZ}{dt} = k_2W^p - k_3Z^q = k_2(c_2 - X - Z)^p - k_3Z^q \tag{6.42}$$

The nonlinear systems of equations (6.40-6.42) can be examined further with phase plane plots. For simplicity, generic phase plane plots are created assuming all exponents (m, n, p) are unitary values equal to 1 as well as constants, c_i as shown in Figures 6.11-6.13. While this assumption does eliminate many of the complexities of a learning model that can capture not only the qualities of the instruction and genetic ability of the individual, the simplification does allow for the evaluation of stability through phase plane plots and as a result does illuminate certain elements of the learning process.

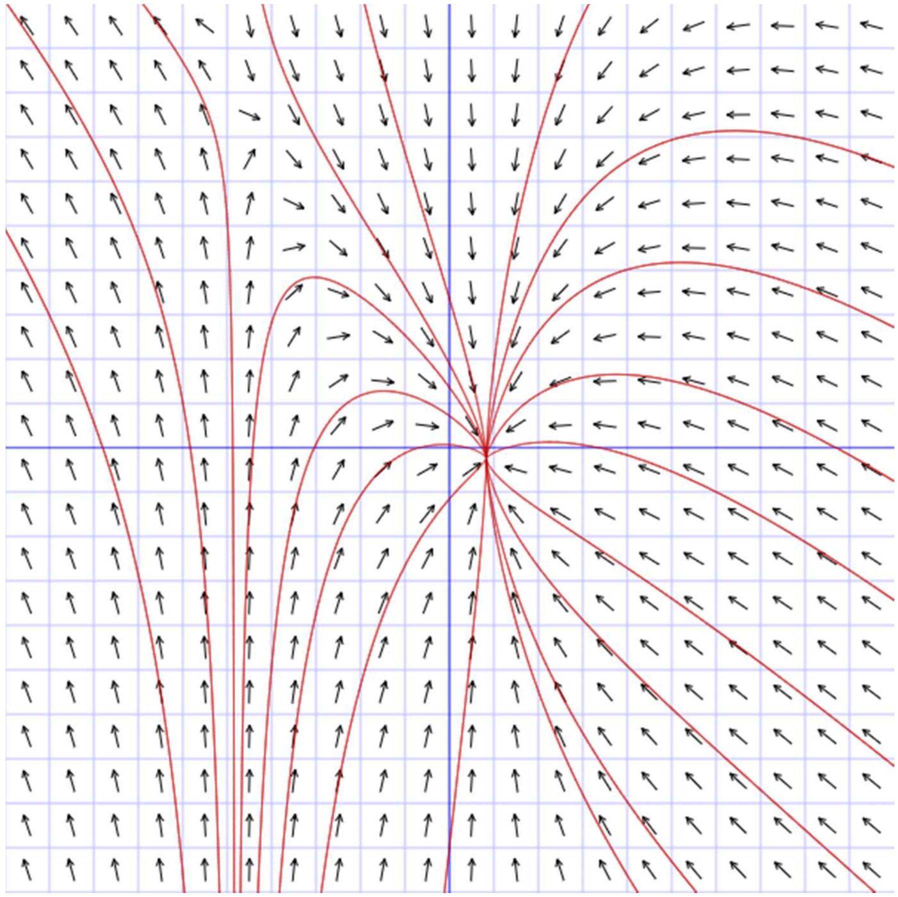

Figure 6.11. Generic phase plane plot of X and W based on the LED model

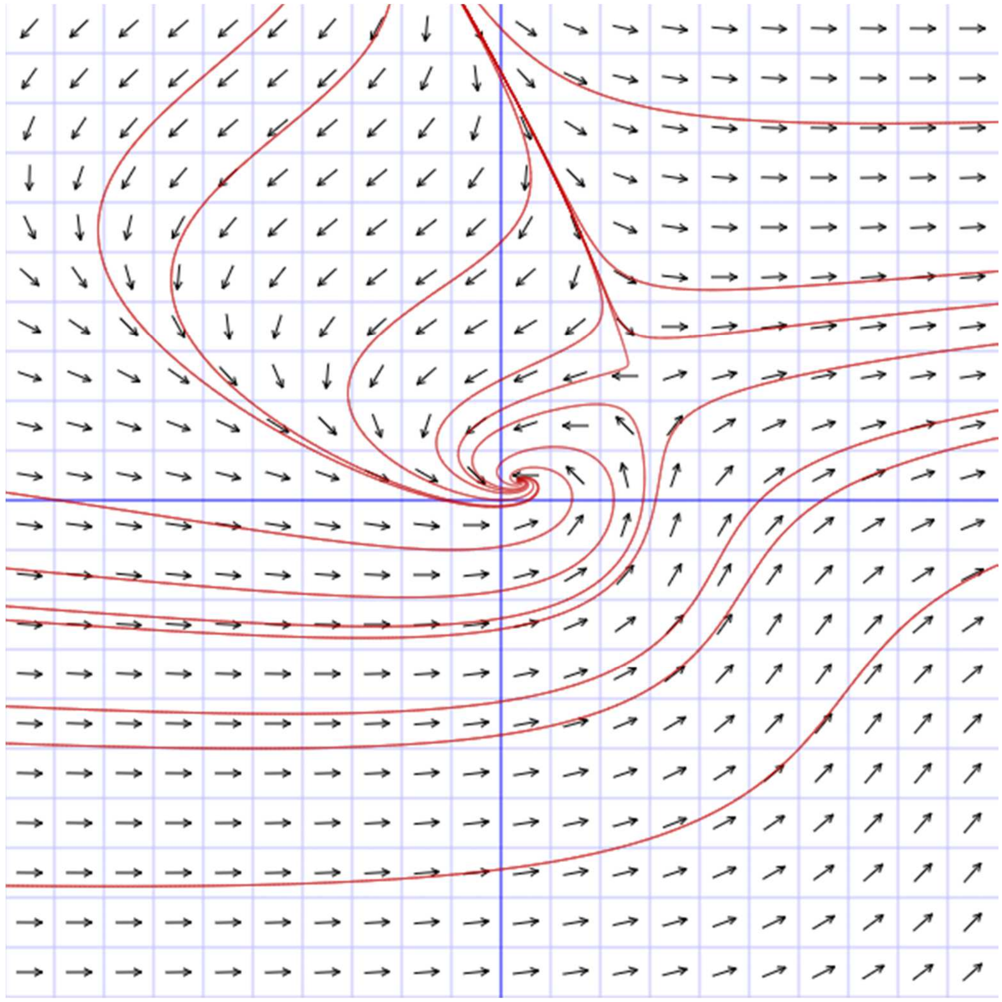

Figure 6.12. Generic phase plane plot of W and *Z* based on the LED model

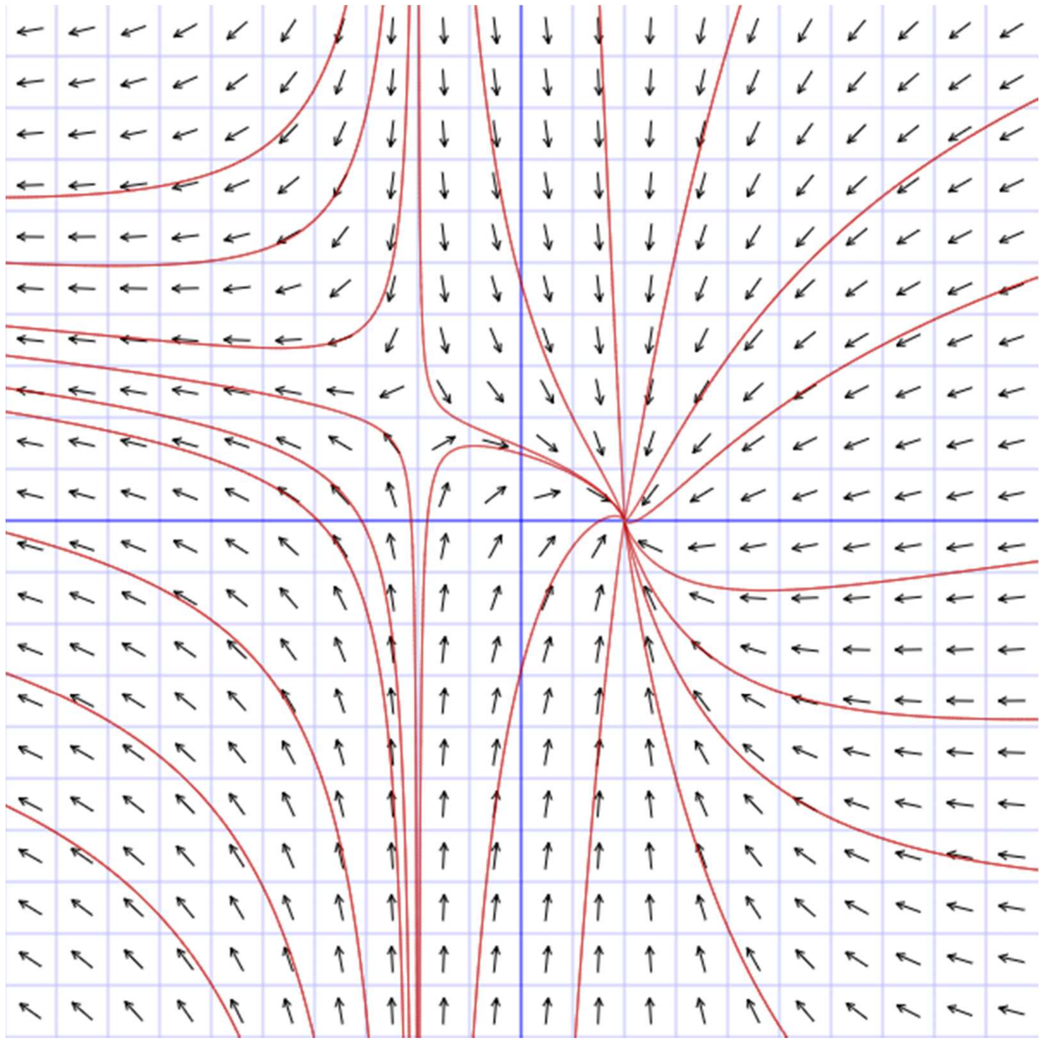

Figure 6.13. Generic phase plane plot of X and Z based on the LED model.

The most interesting observation that are offered by Figures 6.11-6.13 is an analysis of stability. The equilibrium or steady state condition is represented by a critical point and stability can also be observed which represents a degree of permanence in an equilibrium solution. Fig. 6.13 indicates a stable node between the sensory information, X, and the short-term memory, W, similar to the LEKR model. Where the LED model diverges is obvious in the stability analysis of Figures 6.12 and 6.13. While the LEKR model did not offer any stable points of equilibrium, the LED model does clearly indicate the presence of a stable spiral in Figure 6.12 which indicate the presence of an imaginary component of the solution. This could be one possible explanation why thus far a learning model has not been developed as the examination of learning occurring on the imaginary plane has not been done. Most research has been limited to the Cartesian plane of analysis thus far. Figure 6.13 also indicates a stable node between X and Z.

6.4 Conclusion

Of the many mysteries that remain, human cognition and consciousness has likely been the most considered and studied yet remains one of the most mysterious of topics. Indeed, such a topic has been the focus of much research on the human brain including psychology and neuroscience and though significant advancements have occurred, conclusions regarding human consciousness are limited in scope.

The goal of this chapter is to use tools used in the field of applied mathematics to gain an understanding of behavior on six different theoretical learning models that are deterministic instead of stochastic in nature. It is the conclusion of the authors that perhaps we are not equipped with the suitable cognitive capacity to fully understand the mystery of life or do not yet have a thorough enough understanding on biological processes to create a complete mathematical model. As such, it is the goal of this chapter to examine the possibility that the human experience could be captured in the language of nature; mathematics. It is possible that the experience of learning is analogous to the microscale processes happening within Chemistry and that learning is similar to a chemical reaction and can be modeled with reaction kinetics. It is possible that one could come to understand their own individual faculties and calibrate a model of learning so that their experience could be optimized by understanding the related genetic and environmental constants that are present in each of the learning models presented. As presented by Šimon and Bulko, our understanding of forgetting helps us understand the operation of our own brains and how the multitude of external variables effects the ability of our brains to process information and store it [1].

This chapter illustrated that conclusions related to equilibrium conditions and stability on six different learning process models are a valuable first step in the creation of a future model of the learning process. It is not the aim of this chapter to presume that any of these models is fully correct, but instead present each as capturing some limited aspects of the learning process with increasing complexity. By examining each of the six models and highlighting shortcomings, it is possible to imagine the development of a future deterministic model that addresses each of these shortcomings that could be evaluated through the lens of applied mathematics. Such a theoretical model, based upon the understanding that the learning process is a biological process that can be described through chemistry could be tested with empirical data and calibrated for an individual. The existence of such a model would be incredibly useful to an individual in understanding their own limitations in knowledge acquisition but also in optimizing their learning process. The existence of such a model could also revolutionize the educational system as it would allow a means to quantify aspects of the learning process that have heretofore been impossible to measure. Such a future model is undoubtedly ambitious and rightly deserves extreme criticism that the existence is even possible. However, the authors conclude that undoubtedly there is a process in which learning occurs and although complex, it can be described in the language of mathematics and the development of such a model will begin with the analysis of equilibrium and stability.

At this stage, conclusions related to learning are limited in scope and application. One of the most basic functions of humanity – our ability to learn, is not well understood. However, by examining six different learning models presented based upon a form of reaction kinetics, it is possible to understand behavior such as stability through the tools of applied mathematics and thereby illuminate certain layers of human cognition and learning. This analysis becomes the logical first step in the development of a future model of the learning process that is accurate. This chapter was presented and published in the proceedings of the International Conference on Engineering, Science, and Technology (IConEST) in October of 2022 [44].

References

1. J. Šimon, M. Bulko, "A Simple Mathematical Model of Cyclic Circadian Learning", *Journal of Applied Mathematics*, vol. 2014, Article 592587, 9 pages, 2014. https://doi.org/10.1155/2014/592587
2. A. Atkinson, R. Shiffrin, Mathematical Models for Memory and Learning, *Psychology Series: Institute for Mathematical Studies in the Social Sciences*, Technical Report No. 79, Stanford University, 1965.
3. K. Malmberg, J. Raaijmakers, & R. Shiffrin, 50 years of research sparked by Atkinson and Shiffrin (1968). *Mem Cogn* 47, 561–574, 2019. https://doi.org/10.3758/s13421-019-00896-7
4. S. Shikaa & J. Ajai, A Mathematical Model to Study the Human Brain Information Processing Dynamics. *American Journal of Applied Mathematics*. 3. 233. 10.11648/j.ajam.20150305.15.
5. W.J. Hicklin, A model for mastery learning based on dynamic equilibrium theory. *Journal of Mathematical Psychology, 13*(1), 79–88, 1976.
6. R. Bush, F. Mosteller, A Mathematical Model for Simple Learning. In: Fienberg S.E., Hoaglin D.C. (eds) *Selected Papers of Frederick Mosteller. Springer Series in Statistics.* Springer, New York, NY, 2006 https://doi.org/10.1007/978-0-387-44956-2_12
7. R. Anderson, A Neuromathematical Model of Human Information Processing and its applications to Science content acquisition, *Journal of Research in Science Teaching*, Vol. 20, NO. 7, PP. 603-620, 1983.
8. Burros, R. H. Some criticisms of "A mathematical model for simple learning." *Psychological Review, 59*(3), 234–236,1952. https://doi.org/10.1037/h0057645

9. P. Preece, Comments and Criticism Mathematical Modeling of Learning, *Journal of Research in Science Training*, Vol. 21, NO. 9, PP. 953-955. 1984
10. C. Fey, An Investigation of some Mathematical Models for Learning. *Journal of experimental psychology* 61.6 (1961): 455-61. *ProQuest.* Web. 9 Sep. 2021.
11. D. Burini, S. De Lillo, L. Gibelli, Collective learning modeling based on the kinetic theory of active particles, *Physics of Life Reviews*, Volume 16, Pages 123-139, 2016.
12. I. Ormazábal, F. Borotto, H. Astudillo, An agent-based model for teaching–learning processes, *Physica A: Statistical Mechanics and its Applications*, Volume 565, 2021, 125563, ISSN 0378-4371,
13. X. Wu, Y. Zhang, X. Wu, and W. Sun, A Nonlinear Dynamic Model for Individual Learning with Plateau Phenomenon. *In Proceedings of the 2020 11th International Conference on E-Education, E-Business, E-Management, and E-Learning (IC4E 2020)*. Association for Computing Machinery, New York, NY, USA, 109–115. DOI:https://doi.org/10.1145/3377571.3377575
14. W. Fredrick, & H. Walberg. Learning as a function of time. Journal of Educational Research, 73, 183-1 94, 1980.
15. B. Aldridge, A mathematical model of mastery learning. *Journal of Research in Science Teaching*, 20(1), 1-17, 1983.
16. B. Aldridge, K. Johnston, Examining a mathematical model of mastery learning in a classroom setting, *Journal of Research in Science Teaching*, Vol. 22, NO. 6, PP. 543-554, 1985.
17. J. Logan, *Applied Mathematics* (4th Ed). Wiley, 2013.
18. V. Servant-Miklos, Fifty Years on: A Retrospective on the World's First Problem-based Learning Programme at McMaster University Medical School, *Health Professions Education*, 5(1), 2019, Pages 3-12, ISSN 2452-3011, https://doi.org/10.1016/j.hpe.2018.04.002.
19. G. Schmidt, “Foundations of problem-based learning: some explanatory notes”, *Medical Education*, 27(5), 1993, 422-432.
20. E. Graaff, A. Kolmos, “Characteristics of Problem-Based Learning”, *International Journal of Engineering Education,* 19(5), 2003, 657-662.
21. M. Foss and Y.-C. Liu, “Creating solutions through project-based and experimental learning: A case study of the Concept Center”, *International Journal of Engineering Education*, 37(6), 2021, 1630-1642.
22. M. Foss and Y.-C. Liu, “Developing creativity through project-based learning”, Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference, virtual conference, April 15-16, 2021.
23. M. Foss and Y.-C. Liu, “Project-based learning center to bridge to students with technology”, Proceedings of 2020 Intermountain Engineering Technology and Computing (IETC), Orem, UT, USA, September 2020.
24. M. Foss, Y.-C. Liu, S. Yarahmadian, “Project-based learning in engineering education in a virtual setting: A case study on materials and manufacturing process and applied statistics”, *International Journal of Engineering Education*, 39(5A), 2022, 1377-1388.
25. M. Foss and Y.-C. Liu, “Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center”, Proceedings of the 1st International Academy Conference on the Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.

26. M. Foss and Y.-C. Liu, "Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines", Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.
27. Y.-C. Liu, "Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course", *European Journal of Engineering Education*, 42(6), 2017, 800-811.
28. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers, "Theo Jansen project in engineering design course and a design example", *European Journal of Engineering Education*, 36(2), 2011, 187-198.
29. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
30. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, "Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course", *International Journal of Mechanical Engineering Education*, 47(4), 2019, 315-337.
31. Y.-C. Liu and F. Baker, "Development of vibration and control system through student projects", Proceedings of ASEE SE Section Annual Conference, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
32. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 8(1), 2018, 1-18.
33. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 7(2), 2017, 106-122.
34. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.
35. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
36. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
37. Y.-C. Liu, J.A. Batte, Z.H. Collins, J.N. Bateman, J. Atkins, M. Davis, D. Salley, C.L. Bethel, J.E. Ball, and C. Archibald, "Mechanical design, prototyping, and validation of a Martian robot mining system", *SAE International Journal of Passenger Car – Mechanical Systems*, 10(1), 2017, 1289-1297.
38. M. Inzlicht & T. Ben-Zeev, A threatening intellectual environment: Why females are susceptible to experiencing problem-solving deficits in the presence of males. *Psychological Science, 11*(5), 365–371, 2000 https://psycnet.apa.org/record/2000-00950-003

39. T. Schmader & M. Johns, Converging Evidence That Stereotype Threat Reduces Working Memory Capacity. *Journal of personality and social psychology*. 85. 440-52, 2003. 10.1037/0022-3514.85.3.440.
40. K. Rainey, M. Dancy, R. Mickelson, *et al.* Race and gender differences in how sense of belonging influences decisions to major in STEM. *IJ STEM Ed* **5,** 10, 2018.
41. M. Inzlicht, & C. Good, How environments can threaten academic performance, self-knowledge, and sense of belonging. *Stigma and Group Inequality: Social Psychological Approaches*, PP. 129-150, Lawrence Erhbaum Associates Publishers, 2006.
42. M. Inzlicht, & T. Ben-Zeev, A threatening intellectual environment: Why females are susceptible to experiencing problem-solving deficits in the presence of males. *Psychological Science, 11*(5), 365–371, 2000.
43. N. Youssef, et al. "The Effects of Trauma, with or without PTSD, on the Transgenerational DNA Methylation Alterations in Human Offsprings." *Brain sciences* vol. 8,5 83. 8 May. 2018, doi:10.3390/brainsci8050083
44. M. Foss, Y.-C. Liu, and S. Yarahmadian, "An evaluation of mathematical models and stability analysis of learning based on reaction kinetics", Proceedings of the International Conference on Engineering, Science and Technology (IConEST), October 13-16, 2022, Austin, TX, USA.

Chapter 7

PJBL as Means to Promote Social Change

Abstract

The field of engineering is well-suited to solve many of the United Nations 17 Sustainable Development Goals (SDGs). It is the responsibility of institutions of higher learning to prepare engineering students to not only understand their role in achieving these goals but to be equipped with the skills, knowledge, and expertise to make incremental changes and advancements in their field that support sustainable development. One such way to do so is through experience in project-based learning (PJBL). The Concept Center at Weber State University is modeled after PJBL and functions to pair students with sponsored projects. This chapter discusses the application of PJBL in the Concept Center to achieve a double mission of being an active community member by connecting academia with industry and community members and providing opportunities for students to gain needed skills in problem solving and project engineering and mentorship. A summary of past projects completed at the Concept Center by student interns is presented that demonstrate the ability of the PJBL Center to advance goals related to good health and wellbeing (SDG3), quality education (SDG4), gender equality (SDG5), affordable and clean energy (SDG7), and industry, innovation, and infrastructure (SDG9).

7.1 Introduction

The purpose of this chapter is to provide the evidence, framework, and benefits of utilizing a Project-Based Learning (PJBL) center to advance the United Nations SDGs that are relevant and custom to the local community.

PJBL is a pedagogical approach where the learning centers around problems [1]. The Concept Center at Weber State University is designed as a living laboratory for students to gain hands-on experience through PJBL. The Concept Center strengthens the university's time-tested mission of teaching by expanding that mission to include the conversion of knowledge into solutions to real world problems. The Center employs undergraduate student interns from the College of Engineering, Applied Science and Technology (EAST) in a part-time capacity. The Concept Center is organized into two components which represent the mission of the Center:

Education:

The Concept Center is a proving ground for student interns to work on sponsored projects under the direction of faculty mentors. This hands-on experience allows student interns to be better prepared to meet the demands for the modern workforce. By gaining more experience in communication, and broadening their understanding to encompass the economic, social, environmental, and international context of the engineering field, the student intern education is strengthened.

Research and Development:

The Concept Center is a place where new knowledge, technology and capability are constantly being expanded. It can meet a variety of different needs that industry will encounter during their research and development activities ranging from development research to product development.

The Concept Center at Weber State University was not created to address the need to meet the 17 goals, however each project that is detailed in this chapter explicitly does advance one of the 17 goals in parallel with supporting the goal of quality education. By design, the Concept Center is intended to promote quality education but intentionally selects projects and engages in activities that promote good health and wellbeing, gender equality, affordable and clean energy, and industry, innovation, and infrastructure. The application of meeting these goals is customized and relevant to the local community or individual sponsoring the project. By focusing on the goal of quality education, students gain experiences that would be impossible to achieve in a classroom setting working on sponsored projects that function to promote one or more of the SDGs.

7.2 Methodology

This chapter describes the organization, framework, and operation of the Concept Center at Weber State University and provides an example of diverse projects that have been completed and their link to at least one of the SDGs. Foss and Liu have described the benefits of the Concept Center as a means of developing creativity [2] and allowing students to gain skills in technology [3] as well as identifying key benefits to the institution as well as key lessons learned in student intern management and methods in selecting and identifying appropriate projects [4-7]. Liu and colleagues have also had success integrating PJBL methodologies in the classroom setting to improve the learning outcomes of students [8-18].

The projects that are selected by the Concept Center are invariably tied to at least one of the SDGs. Many past projects target the goal of good health and wellbeing that are addressed here. This chapter will also explicitly demonstrate the unique ways the Concept Center advances the goal of quality education through projects, intern mentorship, and outreach to the local community. This chapter will also address the ways that the Concept Center takes an active role in promoting the goal of gender equality by engaging in activities that are designed to promote and support women in engineering. Additionally, this chapter will highlight several completed projects that promote the goals of affordable and clean energy and industry, innovation, and infrastructure.

7.3 Findings

This chapter provides evidence of success by detailing projects completed at the Concept Center that support many of the SDGs including SDG3-5, 7, and 9.

7.3.1 SDG3: Good Health and Wellbeing

The Concept Center has a history of projects that have been completed that promote SDG3.

One example project is the design and prototype of tactile braille display hardware as shown in Figure 7.1. This prototype was completed with an aim of developing a tablet designed for users with visual impairment so that users can utilize technology that has been inaccessible to the blind and visually impaired community. Work on this sponsored project has been completed and delivered to the customer for further improvements in design and usability.

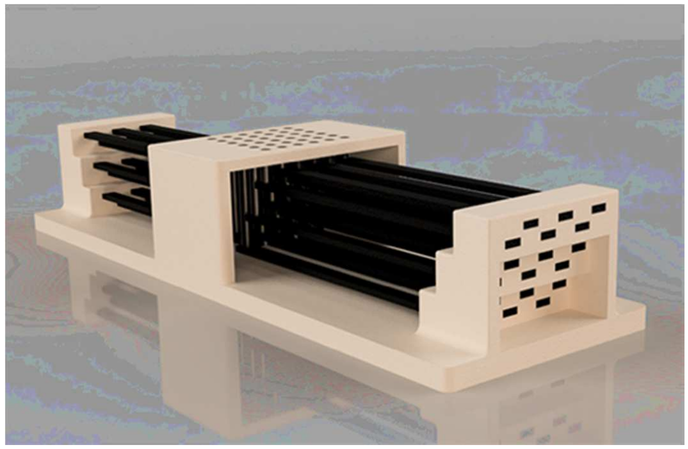

Figure 7.1. Tactile Display Hardware

In another project, the Concept Center designed and fabricated an athletic tape dispenser product for a student that only had one arm that was completing his studies in the athletic training degree. The product needed to accommodate multiple rolls of athletic tape as well as have the ability to cut the tape at custom lengths with one-handed operation. The Concept Center began by looking for solutions that could meet the customer requirements and created a simple and low-cost prototype that was belt-mounted and used a cutting wheel and slider as well as an easy quick-release mechanism for changing and replacing tape rolls as shown in Figure 7.2. This is an example of a project that meets the custom needs of an individual in the community and allows the individual to continue to advance in professions that would otherwise be limited.

Figure 7.3 shows a completed prosthetic guitar pic that was designed and built for a guitar musician that has only one arm. This device was designed with a removable insert so that musician could utilize existing guitar picks. These projects are examples of projects that the Concept Center engages in that allow for the use of technology to solve real problems related to the health and wellbeing of members of the community.

Figure 7.2. Athletic Tape Dispenser for one-armed operation

Figure 7.3. Prosthetic Guitar Pick

Figure 7.4 shows the completed prototype of another project that had very unique requirements. A group of philanthropic eye doctors wished to come up with a device to administer an eye exam in a field setting. These doctors intended to travel to low income areas and Native American tribal lands to administer eyes tests for residents in those communities. They needed a product that could easily disassemble and fit in carry-on luggage, be light-weight, and low-cost and allow for customizable settings to complete the exam. The Concept Center, working in conjunction with a team from the University of Utah designed and built a prototype that met the needs of the customers as shown in Figure 7.4.

Figure 7.4. Eye Exam Stand

The Concept Center has also worked on a number of projects that are subject to non-disclosure agreements (NDAs) and cannot be discussed in detail such as an innovative intubation tool. This tool is designed to aide a healthcare provider in keeping the airway open so air can get to the lungs in high risk and specialized populations of patients. Many projects completed by the Concept Center are selected due to their ability to promote SDG3.

7.3.2 SDG4: Quality Education

7.3.2.1 Improving Educational Outcomes

Many successful projects completed through the Concept Center have resulted in significant advancements in teaching within Weber State University and improvements in educational outcomes. In these projects, the clients are faculty or staff members of the University who were looking for solutions for their courses to improve the quality of the education of the course. A few examples of the developed teaching aids are Deming's Red Bead experiment for the course Quality Concepts and Statistics in the Manufacturing Systems Engineering (MSE) Department, I-beam molds for laboratory use in the course Reinforced Plastics/Advanced Composites in the MSE department, 3D printed self-assembling bacteria for Introductory Microbiology in the Microbiology Department shown in Fig. 7.5, Leidenfrost effect blocks for several courses in the Physics Department, and a laser pointer assessment tool for the course Human Anatomy in the Zoology Department shown in Fig. 7.6. Lastly, three senior project teams in the Mechanical Engineering Department engaged in an autonomous robot competition where each team had to design a robot that would follow a course and launch a projectile at a target from different pre-determined locations. The Concept Center designed and fabricated a table-height 9-foot by 10-foot flat seamless surface equipped with side barriers and target locations that could be easily stored compactly when not in-use for use in the robotics course competition.

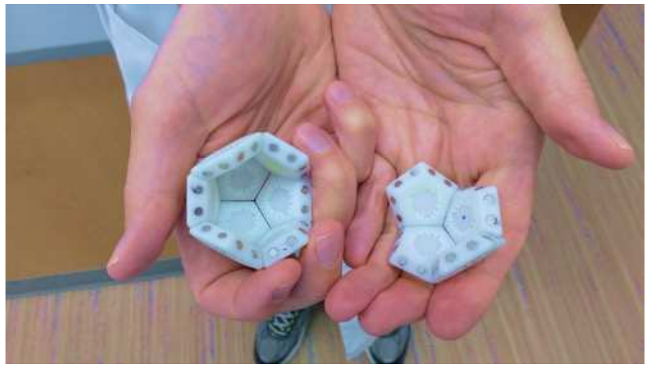

Figure 7.5. Self-assembling Bacteria

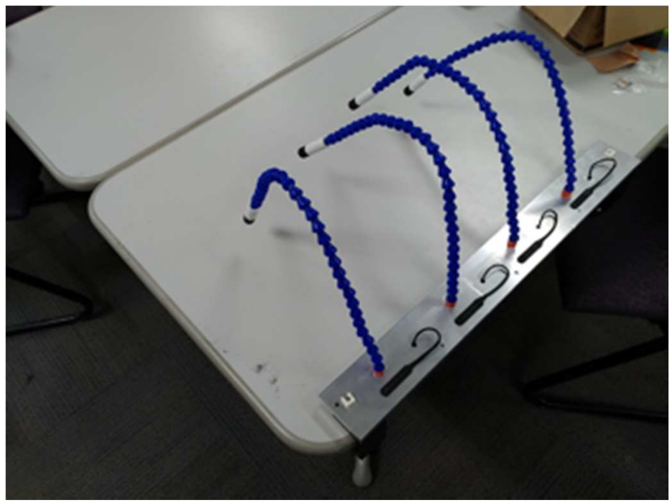

Figure 7.6. Laser Pointer Assessment Tool

Another example of projects completed that are aimed at improving student learning outcomes is demonstrated by the cadaver storage system. The Zoology Department at Weber State University received two cadavers by donation for use as teaching aids. A faculty member in that department wanted to use these cadavers in undergraduate human anatomy courses but did not have a way to store them. Moreover, the department did not have a budget or funding access to purchase a cadaver storage system. The Zoology faculty member approached the Concept Center for help with a temporary and a long-term storage solution for the cadavers. Based on the customer's requirements, the team began by dividing this project into two phases. The goal of the first phase was to provide a short-term solution for the summer term and the goal of the second phase was to develop a long-term solution for permanently storing the cadavers in the Zoology Department. The Concept Center delivered to the Zoology department a low-cost and short-term solution and a longer-term solution that involved redesigning an existing gurney and equipping it with a pump and recirculating spray system as shown in Fig. 7.7. There were several important learning outcomes and unique design features included in this project that Foss and Liu have detailed [4].

Figure 7.7. Cadaver Storage Solution.

Another project that was completed was the development of a mold for a mannequin shoulder insert. A faculty member from the Department of Zoology wanted a mold that could be used to make gel shoulder inserts for a mannequin for a continuing medical education (CME) accredited class for the Ogden Surgical-Medical Society's 2018 annual meeting. The gel shoulder inserts would be used in a technical training course for attendees led by a faculty member from the University. The mold was designed to allow attendees who are doctors, nurse practitioners, and physician assistants to practice injecting corticosteroids into various joints of the shoulder that are prone to damage. In this technical training course, CME students could visually see the location where the dye was delivered to simulate an injection of medicine on a real shoulder. Using the mannequin provided by the Zoology faculty, the team made a reusable silicon mold. Fig. 7.8 shows the mold made in progress for the mannequin shoulder.

Figure 7.8. Mannequin shoulder mold teaching aid in progress

7.3.2.2 Mentoring Student Interns

Student interns can benefit the most from the PJBL center through the mentoring relationship. The importance of mentoring experiences cannot be overstated and yet it rarely receives the focus or attention in academic culture [19]. At the Concept Center, each student will have varying and individual needs. One student may need instructions on research methodologies or the use of technology. Fig. 7.9 shows students gaining skills in the operation of a CNC Plasma Cutting table. Another student may need guidance in interpersonal and communication skills. It is the responsibility of the mentor to assess the needs of each student intern and guide them accordingly. The role that the mentor plays should be tailored for each student intern. Each mentor should meet with student interns individually, document their goals of development, and discuss ways of assessing their progress.

Figure 7.9. Students gaining skills in technology through mentoring

7.3.2.3 Active Community Member

The Concept Center plays an active role in advancing quality education by volunteering to host sessions at local elementary schools for science fairs and STEM days. Faculty and interns at the Concept Center design PJBL related challenges and provide materials to elementary-age children for STEM day

Concept Center faculty also engage in judging science fairs at local elementary schools and mentoring of winning students as they progress to the next level of the science fair. To do so, one faculty member met individually with 17 6^{th} grade students and provided them tailored feedback and coaching to improve their poster, scientific method and presentation delivery. Many of these students received ribbons and advanced to the regional science fair that is scheduled for late spring, 2022. In this way, The Concept Center can promote SDG4 to not only the institution but also the local community.

7.3.3 SDG5: Gender Equality

The Concept Center plays an active role in promoting SDG5 by supporting women in engineering through outreach activities. The role that women have played in the field of engineering is historically complex but is also changing. In 2007 in the United States, 2.6% of freshmen women had intentions to major in Engineering compared to 13.7% for men. By 2014, the percentage of freshmen women intentions increased to 5.8% while for freshmen men the intentions increased to 19.1% [20]. These increases in both genders show a marked improvement that could be attributed to many factors, including focus on Science, technology, engineering and math (STEM) in primary and secondary education. However, despite these advances, there remain interesting trends in retention of underrepresented minorities (URM) students in STEM fields. Proportionally, 32% of females left STEM fields by switching to a non-STEM major compared to 26% for males [21]. There also exist significant gender imbalances within these fields in both the educational setting as well as industry. For example, the percentage of women working as engineers is 8.7% for mechanical and 11.8% for electrical and electronics [22]. The stark gender imbalances within engineering disciplines creates a catch-22 situation. More women would be represented in the educational setting and in industry if a critical mass of women could be achieved, eliminating or reducing challenges related to stereotypes and stereotype threat and belonging. The Concept Center prioritizes promoting SDG5 within engineering by engaging in a number of outreach events sponsored by the University that are designed around PJBL and also intended to create an environment that where belonging is fostered.

7.3.3.1 Parent Daughter Engineering Night

Many agree that a parent is a child's first teacher. The inspiration for the Parent Daughter Engineering Night Event hosted by Weber State University is based upon this premise using principles of problem-based learning (PJBL). This event has been hosted for a period of eleven years with the past 5 years including Foss, the director of the Concept Center, as an event planner and facilitator.

In the setting created by the event, parents see their daughter in a positive atmosphere that not only supports but demonstrates the place of women in engineering. Additionally, the daughter, with a target age group of grades 7 through 12, can find herself in a group of her peers engaging in hands-on engineering activities and hearing the stories of women in engineering as students or in their careers. The result is both parties can share in an experience that uplifts and supports women in engineering and visualize a potential future for the daughter in engineering. Figs. 7.10 and 7.11 demonstrate the inclusive nature of the event, the application of PJBL in the event design and the culture that is fostered to promote gender equality for women in engineering.

Figure 7.10. Parent-Daughter Team solving PJBL Challenge

Figure 7.11. Daughters presenting their PJBL Hydraulic hand challenge

7.3.3.2 Girls Welding Camp

Another outreach event that has been supported by the Concept Center is a summer camp that is hosted by Weber State University is the Art and Science of Metalwork through the medium of welding. This hands-on overnight camp targets 7-12th grade girls and exposes students to metal inert gas (MIG) welding, computer aided design (CAD), metal cutting processes such as plasma and waterjet cutting. The Concept Center supports this camp by serving as an instructor, planning the PJBL design and build challenges completed by the students, and preparing materials needed for the camp. Figs. 7.12 and 7.13 show attendees of the camp participating and learning the welding process in an environment that is inclusive and designed to promote gender equality in a field where there is minimal representation from women.

Figure 7.12. Attendees of Welding Camp

Figure 7.13. Student Welding Art Project

7.3.4 Affordable and Clean Energy

The Concept Center prioritizes projects that target SDG7. One example project that was completed was the design and fabrication of two solar powered pavilions. The goal of the Solar Pavilion project was to design and fabricate two solar powered pavilions equipped with lighting and charging sources to power electronic devices. The primary goal of this project was to provide a safe and attractive place for students to convene, study, and work together outside. There were no such areas for students on the campus at that time and the cost of installation to run a new power line to a remote part of the campus was prohibitive and against the campus goals of sustainability.

At the completion of this project, two solar pavilions were installed on campus. Student interns gained hands-on experience in design and fabrication of the corrosion-resistant metal structures and accompanying solar power lighting and charging stations.

In carrying out this project, they also developed skills in troubleshooting, teamwork, and problem solving. One completed solar pavilion with a student user is shown in Fig. 7.14. The pavilions have been in operation since June of 2019. The Concept Center has been monitoring their performance since then and has verified from student feedback that the solar powered pavilions function well in providing lighting and outdoor charging access for students.


Figure 7.14. Completed solar pavilion

This project led to another partnership with a community partner to design and build a solar powered bus stop shown in Fig. 7.15. This bus stop was designed to utilize clean energy (solar) to power a light and an electronic display screen that could display the bus schedule as shown in Fig 7.16.

Figure 7.15. Solar Powered Bus Stop

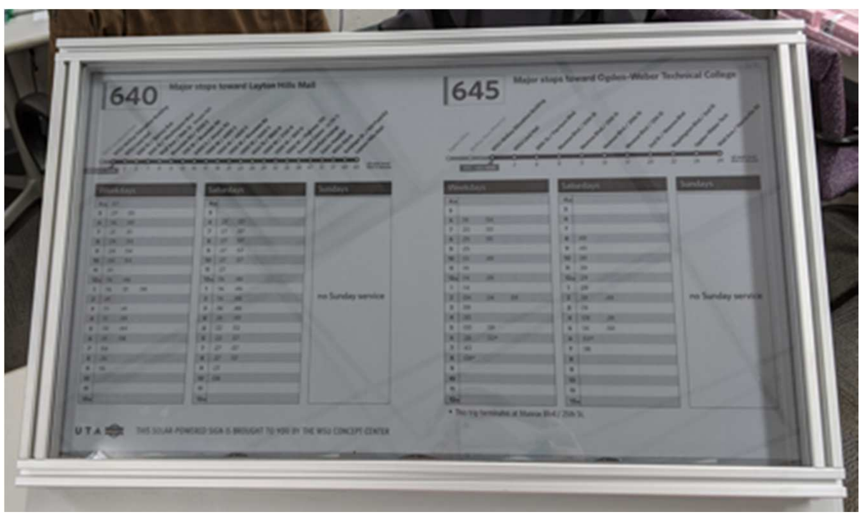

Figure 7.16. Solar Powered Programmable Display Screen

7.3.5 Industry, Innovation, and Infrastructure

The majority of the industrial partners that have sponsored projects completed at the Concept Center are subject to NDAs so cannot be discussed here. There are, however, some projects that have been completed to support research projects that can be detailed.

Fig. 7.17 shows the CAD rendering of a test fixture device intended for a start-up corporation working on an innovative vehicle system. This test fixture was designed and fabricated by the Concept Center and allowed the company to better understand weak areas of their design by allowing the component to be tested to failure in an INSTRON machine. Loading conditions that will simulate its use were applied to the device and the customer was able to determine that the component needed to be redesigned to handle the loading that it will experience in use.

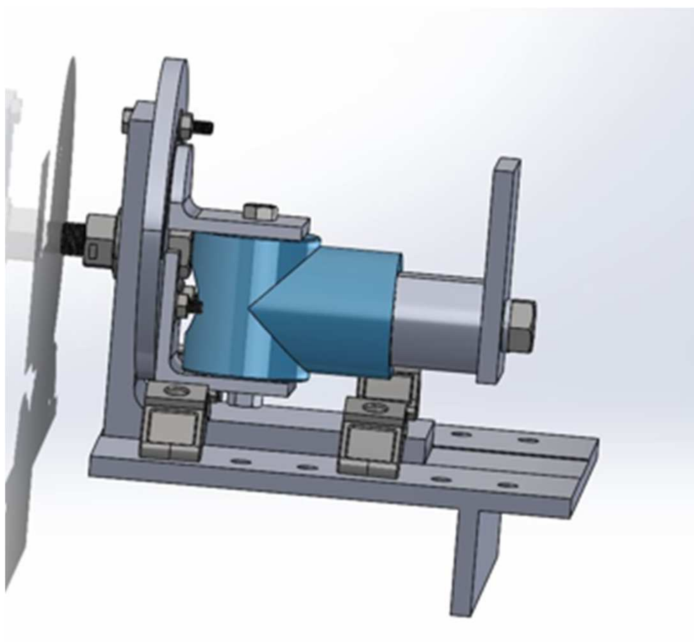

Figure 7.17. Test Fixture

Fig. 7.18 shows the completed devices designed and built by the Concept Center to test the water quality at a high elevation lake in a sensitive environment in Utah. Fish Lake is located adjacent to Pando, a clonal quaking aspen believed to be the largest living organism on the planet in Fish Lake National Forest [23] as shown in the image in Fig. 7.19. A team of researchers were engaged in evaluating the water quality of nearby Fish

Lake and needed a device that could be affixed to a dock and monitor the water surface as the level changes.

Figure 7.18. Water Quality Device

Fig 7.19. Pando (USDA Forest Service, 2022)

7.4 Conclusion

This chapter details the relevance of the Concept Center to support the goals of SDG3-5, 7 and 9 through past projects completed.

By understanding the impact of the Concept Center at Weber State University to the local community, other institutions can develop their own PJBL centers and further advance the United Nations SDGs in a manner that is custom to their local community. In order for the 17 goals to be achieved, academic institutions must take incremental steps and make progress in areas that are directly related to their communities. A PJBL Center similar to the Concept Center is a practical way to do so and this chapter demonstrates the explicit ways the goals can be accomplished through completed projects.

Acknowledgements

This chapter is authored based upon projects completed at the Concept Center at Weber State University located in the College of EAST. The authors would like to express their gratitude for the help and support from the following student interns, faculty members, and staff: Thomas Odenwalder, Brandon Burke, Joshua Lepus, Austin Byrer, Kaitelyn Whiting, Jacqueline Fessler, Nathaniel Pope, Taylor Foss, Dr. David Ferro, James Taylor, Justin Knighton, Patrick Thomas, Gina Naisbitt, George Comber, Jason Manley, Jeff Strahan; and industry and community sponsors: Hill Airforce Base, Murphy Door, ATK, Hydropur, GSC Foundries, Dr. Brian Chung, and SES Engineering.

References

1. J. Krajcik, & P. Blumenfeld. 2005. Project-Based Learning. In R. Sawyer (Ed.), The Cambridge Handbook of the Learning Sciences (Cambridge Handbooks in Psychology, pp. 317-334). Cambridge: Cambridge University

2. M. Foss and Y.-C. Liu, 2021. Developing creativity through project-based learning. *Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference*, virtual conference, April 15-16, 2021.
3. M. Foss and Y.-C. Liu. 2020. Project-based learning center to bridge to students with technology. *Proceedings of 2020 Intermountain Engineering Technology and Computing (IETC*), Orem, UT, USA, September 2020.
4. M. Foss and Y.-C. Liu. 2021. Creating solutions through project-based and experimental learning: A case study of the Concept Center. *International Journal of Engineering Education*, 37(6), 1630-1642.
5. M. Foss, Y.-C. Liu, and S. Yarahmadian, "Project-based learning in engineering education in a virtual setting: A case study on materials and manufacturing process and applied statistics", accepted by *International Journal of Engineering Education*, 39(5A), 2022, 1377-1388.
6. M. Foss and Y.-C. Liu, "Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center", Proceedings of the 1st International Academy Conference on the Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.
7. M. Foss and Y.-C. Liu, "Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines", Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.
8. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers. 2011. Theo Jansen project in engineering design course and a design example, *European Journal of Engineering Education*, **3**6(2), 187-198.
9. Y.-C. Liu and Y.-Q. Dou.. 2015. Design of an industry-tied and team-oriented course for mechanical engineering seniors, *Proceedings of ASEE SE Section Annual Conference*, University of Florida, Gainesville, FL, April 12-14, 2015.
10. Y.-C. Liu, V. Meghat, and B. Machen. 2017. Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach, *International Journal of Design Engineering*, **7**(2), 2017, 106-122.
11. Y.-C. Liu, J. A. Batte, Z. H. Collins, J. N. Bateman, J. Atkins, M. Davis, D. Salley, C. L. Bethel, J. E. Ball, and C. Archibald. 2017. Mechanical design, prototyping, and validation of a Martian robot mining systems, *SAE International Journal of Passenger Cars-Mechanical Systems*, **10**(1), 1289-1297.
12. Y.-C. Liu. 2017. Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course, *European Journal of Engineering Education*, **42**(6), 800-811.
13. Y.-C. Liu, V. Meghat, and B. Machen. 2018. Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an engineering systems design approach. *International Journal of Design Engineering*, **8**(1), 1-18.
14. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.

15. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
16. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
17. Liu, Y.-C, Baker, F., He, W.P., and Lai, W. 2019. Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course, *International Journal of Mechanical Engineering Education*, **47**(4), 315-337.
18. Liu, Y.-C, Baker, F. 2019. Development of vibration and control system through student projects. *Proceedings of ASEE SE Section Annual Conference*, North Carolina State University, Raleigh, NC, March 10-12, 2019.
19. National Academies of Sciences. Engineering, and Medicine; Policy and Global Affairs; Board on Higher Education and Workforce; Committee on Effective Mentoring in STEMM; Dahlberg ML, Byars-Winston A, editors. Washington (DC): National Academies Press (US); 2019 Oct 30.
20. National Science Board. Science and Engineering Indicators 2016, Appendix Table 2-16.
21. X. Chen. 2013. U.S. Department of Education. STEM attrition: College students' paths into and out of STEM fields. [Online]. [Accessed 5 April 2022]. Available from: https://nces.ed.gov/pubs2014/2014001rev.pdf
22. United States Bureau of Labor Statistics. Labor Force Statistics from the Current Population Survey: Employed persons by detailed occupation, sex, race, and Hispanic or Latino ethnicity, [Online]. [Accessed 5 April, 2022]. Available from: https://www.bls.gov/cps/cpsaat11.htm.
23. United States Department of Agriculture Forest Service. Pando. [Online]. [Accessed 5 April, 2022] Available from: https://www.fs.usda.gov/detail/fishlake/home/?cid=STELPRDB5393641

CHAPTER 8

CONCLUSION

This study explores the uses of PJBL in non-traditional learning settings in engineering education by examining the application of PJBL in non-classroom settings, non-traditional classroom settings (virtual or online), how it is supported by theories of learning and how it is a useful tool to achieve social change.

8.1 PJBL in Non-Classroom Settings

Through the exploration of PJBL in these sub-topics, it is shown that using PJBL as a means of promoting Underrepresented Minorities can be achieved through targeted events such as Parent Daughter Engineering night hosted by Weber State University. Using PJBL challenges, parents and daughters are exposed to fun engineering challenges in a supportive environment.

The use of PJBL in the philosophy of the Concept Center at Weber State University is also explored. This study shows that an on-campus center based upon PJBL pedagogy is a useful and successful format that provides numerous benefits to the University as well as the community partners and students. This study details example projects and related learning outcomes that can be achieved as well as highlights key lessons learned in the operation of such a center and management of student interns.

This study also provides a framework and evidence that supports the use of PJBL in developing creativity in engineering education. Each of the 10 maxims of creativity in engineering education are examined and explored and evidence is provided as to how

PJBL can serve each of these maxims through examples of completed past projects at the Concept Center at Weber State University.

8.2 PJBL in Non-Traditional Classroom Settings

Another objective of this study was to examine how principles of PJBL can be integrated into non-traditional classroom settings. Modern engineering education often includes a virtual or online format and this study wanted to explore a practical application of how such a learning environment can be created in a distance setting. This study includes an example of a PJBL challenge that bridges course content between materials science, manufacturing processes and applied statistics to provide students with an interesting challenge to determine the root cause of product failure. This challenge is detailed as well as lessons learned and could be replicated in other institutions.

8.3 PJBL Supported Through Theories of Learning

Understanding the learning process is also critical in understanding the use of PJBL in engineering education. While there are many theories of learning, this topic is still largely unexplored and there exists no fundamental understanding or theory of the chemical and biological process that could explain how learning occurs. Many learning theories are based upon empirical data so one goal of this study was to present hypothetical learning models that are based upon chemical reaction kinetics that could capture what is intuitively understood about the learning process. Using 6 different learning models based upon Reaction kinetics, tools of applied mathematics are employed to understand limitations and conclusions of the models.

8.4 PJBL to Advance Social Change

The goal and objective of the fields of engineering is to improve the quality of life and solve problems. There is perhaps no better way to examine this objective than to consider the United Nations Sustainable Development Goals. These goals represent the global challenges that our modern society faces. This chapter explores the suitability of using PJBL as a model to solve these challenges by examining SDG3-5, 7 and 9 through past PJBL projects completed. In order for the 17 goals to be achieved, academic institutions must take incremental steps and make progress in areas that are directly related to their communities. A PJBL Center similar to the Concept Center is a practical way to do so and this chapter demonstrates the explicit ways the goals can be accomplished through completed projects.

8.5 Future Work

Much of the research on PJBL in engineering education is applied research and takes the form of a case-study. Due to the customized and often, one-time approach of PJBL challenges, it is challenging to incorporate quantitative mixed-methods research in this area. This is largely due to limited data, the need of additional funding as well as control studies to establish effectiveness. There are, however, a number of investigations that could be performed that would strengthen the conclusion of this work by better establishing the effectiveness of the methods discussed. These future investigations are summarized below in Table 1. Without this additional quantitative data, conclusions about the effectiveness of the methods discussed will be limited in scope and application.

Table 1: Future Work in PJBL in Non-Traditional Settings in Engineering Education

Subject Area	Assessment Method	Justification

PJBL in Engineering Outreach	Parent and Daughter Pre- and Post Attendance Surveys	The objective of the Parent daughter engineering night is to demonstrate the place of women in engineering through an environment of belonging. This could be assessed by examining participant views of women in engineering prior to the event and at the conclusion of the event through the use of a survey tool.
PJBL Center to benefit University, Community, Industry Partners	Documented project completion with benefits highlighted and demonstrated	Since each project completed has differing objectives, time frames, scopes, and resources required, this claim will be best demonstrated with more evidence. The proportion of projects completed that provide these benefits could be documented. A metric could be created that could establish a minimum number of projects that meet at least one of the stated benefits and then used for annual assessment of the program.
PJBL to Develop Creativity	Intern Creativity assessment prior to job assignment and after at set intervals	There are several assessment tools for creativity that could be evaluated. The Torrance Tests of Creative Thinking (TTCT) is the most widely used and validated divergent thinking test [1]. This would be a useful assessment tool to measure any change of creativity of participants in PJBL challenges.
PJBL in a Virtual Setting	Learning outcome assessment in PJBL course and non-PJBL course	This is a common way that PJBL has been assessed in research. A study is performed comparing the performance in desired learning outcomes in students exposed to a PJBL challenge and students not engaging in PJBL challenges.
Mathematical Models of Learning Supporting PJBL	Calibration of model variables based upon learning outcome assessment.	Create a unique PJBL learning experience with assessment of short-term and long-term learning built-in. Conduct a study of research participants to understand model input variables and calibrate model based upon empirical data.
PJBL to Advance Social Change	Documented project completion with	Each project completed may support differing SDGs. This claim will be best

	benefits highlighted and demonstrated	demonstrated with more evidence. The proportion of projects completed that support the SDGs should be documented. A metric could be created that could establish a minimum number of projects that meet at least one of the SDGs and then used for annual assessment of the program.

The use of PJBL in engineering education will continue to grow and expand into classroom and non-classroom settings. Research shows PJBL it as a viable solution to achieve the 21st century objectives of engineering education. While the challenges of implementing PJBL in classroom settings will remain, additional opportunities can be provided to students by expanding PJBL in non-traditional settings. By focusing this work on non-traditional applications of PJBL, more evidence is presented to justify the use of PJBL in engineering education.

References

1. J.A. Plucker, G.R. Waitman, K.A. Hartley, *Education and Creativity*, Editor(s): Mark A. Runco, Steven R. Pritzker, Encyclopedia of Creativity (Second Edition), Academic Press, 2011, Pages 435-440, ISBN 9780123750389.

REFERENCES

1. National Science Board, Science and Engineering Indicators 2016, Table 2-16.
2. National Science Board. *Science and Engineering Indicators 2016*, Table 2-17.
3. Chen, X. (2013). STEM attrition: *College students' paths into and out of STEM fields.*
4. United States Bureau of Labor Statistics. Labor Force Statistics from the Current Population Survey: Employed persons by detailed occupation, sex, race, and Hispanic or Latino ethnicity, https://www.bls.gov/cps/cpsaat11.htm.
5. M. Inzlicht, T. Ben-Zeev "A threatening intellectual environment: Why females are susceptible to experiencing problem-solving deficits in the presence of males", *Psychological Science, 11*(5), 365–371. 2000. https://psycnet.apa.org/record/2000-00950-003
6. T. Schmader, M. Johns, "Converging Evidence That Stereotype Threat Reduces Working Memory Capacity", *Journal of personality and social psychology*. 85. 440-52. 2003.
7. K. Rainey, M. Dancy, R. Mickelson, *et al.* "Race and gender differences in how sense of belonging influences decisions to major in STEM". *IJ STEM Ed* **5,** 10, 2018.
8. M. Inzlicht, C. Good, "How environments can threaten academic performance, self-knowledge, and sense of belonging", *Stigma and Group Inequality: Social Psychological Approaches*. PP 129-150, 2006
9. B. Major, L. O'Brien, "The Social Psychology of Stigma", *Annual review of psychology*. 56. 393-421, 2005.
10. S. Spencer, C. Steele, D. Quinn, "Stereotype Threat and Women's Math Performance", *Journal of Experimental Social Psychology*, Volume 35, Issue 1, 1999, Pages 4-28,
11. C. Good, J. Aronson, J. Harder, "Problems in the Pipeline: Stereotype Threat and Women's Achievement in High-Level Math Courses*", Journal of Applied Developmental Psychology*. 29. 17-28, 2008.
12. D. Quinn, S. Spencer, "The interference of stereotype threat with women's generation of mathematical problem-solving strategies", *Journal of Social Issues*. 57. 55-71, 2001.
13. V. Servant-Miklos, Fifty Years on: A Retrospective on the World's First Problem-based Learning Programme at McMaster University Medical School, *Health Professions Education*, 5(1), 2019, Pages 3-12, ISSN 2452-3011,
14. G. Schmidt, "Foundations of problem-based learning: some explanatory notes", *Medical Education*, 27(5), 1993, 422-432.
15. E. Graaff, A. Kolmos, "Characteristics of Problem-Based Learning", *International Journal of Engineering Education,* 19(5), 2003, 657-662.
16. M. Foss and Y.-C. Liu, "Creating solutions through project-based and experimental learning: A case study of the Concept Center", *International Journal of Engineering Education*, 37(6), 2021, 1630-1642.
17. M. Foss and Y.-C. Liu, "Developing creativity through project-based learning", Proceedings of Wasatch Aerospace and Systems Engineering Mini-Conference, virtual conference, April 15-16, 2021.

18. M. Foss and Y.-C. Liu, "Project-based learning center to bridge to students with technology", Proceedings of 2020 Intermountain Engineering Technology and Computing (IETC), Orem, UT, USA, September 2020.
19. M. Foss and Y.-C. Liu, "Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center", Proceedings of the 1st International Academic Conference on the United Nations Sustainable Development Goals, October 5 – 7, 2022, Utah Valley University, Orem, UT, USA.
20. M. Foss and Y.-C. Liu, "Lessons Learned from 5 Years of Parent Daughter Engineering Outreach: Using Project-Based Learning to Introduce Families to Engineering Disciplines", Proceedings of 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, June 26 – 29, 2022.
21. M. Foss, Y.-C. Liu, and S. Yarahmadian, "Project-based learning in engineering education in a virtual setting: A case study on materials and manufacturing process and applied statistics", *International Journal of Engineering Education*, 38(5A), 2022, 1377-1388.
22. M. Foss, Y.-C. Liu, S. Yarahmadian, "An Evaluation of Learning Based upon Reaction Kinetics," International Conference on Engineering, Science and Technology, October 13-16, 2022, Austin, Texas.
23. M. Foss and Y.-C. Liu, "Promoting Sustainable Development Goals through Project-Based Learning: A Case Study of the Concept Center", Proceedings of the 1st International Academic Conference of the Sustainable Development Goals In partnership with the Civil Society Unit and the Academic Impact Initiative of the United Nations Department of Global Communications , Utah Valley University, Orem, UT, October 5-7, 2022. https://www.uvu.edu/global/docs/wim22/sdg9/sdg9-foss.pdf.
24. Y.-C. Liu, "Renovation of a mechanical engineering senior design class to an industry-tied and team-oriented course", *European Journal of Engineering Education*, 42(6), 2017, 800-811.
25. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
26. Y.-C. Liu, A. Artigue, J. Sommers, and T. Chambers, "Theo Jansen project in engineering design course and a design example", *European Journal of Engineering Education*, 36(2), 2011, 187-198.
27. Y.-C. Liu and Y.-Q. Dou, "Design of an industry-tied and team-oriented course for mechanical engineering seniors", Proceedings of ASEE SE Section Annual Conference, University of Florida, Gainesville, FL, USA, April 12-14, 2015.
28. Y.-C. Liu, F. Baker, W.-P. He, and W. Lai, "Development, assessment and evaluation of laboratory experimentation for a mechanical vibrations and controls course", *International Journal of Mechanical Engineering Education*, 47(4), 2019, 315-337.
29. Y.-C. Liu and F. Baker, "Development of vibration and control system through student projects", Proceedings of ASEE SE Section Annual Conference, North Carolina State University, Raleigh, NC, USA, March 10-12, 2019.
30. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of a debris clean and collection system for a cylinder block assembly conveying line following an

engineering systems design approach", *International Journal of Design Engineering*, 8(1), 2018, 1-18.

31. Y.-C. Liu, V. Meghat, and B. Machen, "Design and prototyping of an in-situ robot to clean a cylinder head conveying line following an engineering systems design approach", *International Journal of Design Engineering*, 7(2), 2017, 106-122.
32. Y.-C. Liu, V. Meghat, B. Machen, and G. He, "Design and prototyping of cleaning systems for cylinder head and engine block conveying lines", SAE Technical Paper 2018-01-1387, Proceedings of SAE 2018 World Congress & Exhibition, Detroit, MI, USA, April 10-12, 2018.
33. Y.-C. Liu, G. He, and T. Sippel, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", *SAE International Journal of Aerospace*, 11(1), 2018, 61-69.
34. Y.-C. Liu, T. Sippel, and G. He, "Improve heat resistance of composite engine cowlings using ceramic coating materials, experimental design and testing", SAE Technical Paper 2017-01-2130, Proceedings of SAE 2017 AeroTech Congress & Exhibition, Fort Worth, TX, USA, September 26-28, 2017.
35. Y.-C. Liu, J.A. Batte, Z.H. Collins, J.N. Bateman, J. Atkins, M. Davis, D. Salley, C.L. Bethel, J.E. Ball, and C. Archibald, "Mechanical design, prototyping, and validation of a Martian robot mining system", *SAE International Journal of Passenger Car – Mechanical Systems*, 10(1), 2017, 1289-1297.
36. A. Ben-Zeev, et. al. 'Speaking Truth Protects Underrepresented Minorities' *Intellectual Performance and Safety in STEM. Education sciences,* 7(2), 65, 2017.
37. A. Martens, M. Johns, J. Greenberg, J. Schimel 'Combating stereotype threat: The effect of self-affirmation on women's intellectual performance', *Journal of Experimental Social Psychology*, vol. 42, no. 2, pp. 236-243, 2006.
38. *The Green Report: Engineering education for a changing world*, American Society of Engineering Education, Washington DC, 1994.
39. *Criteria for Accrediting Engineering Programs*, Engineering Accreditation Commission of the Accreditation Board of Engineering and Technology, ABET, Baltimore, Maryland, 2001.
40. J. Mills and D. Treagust, Engineering Education – Is Problem-Based or Project-Based Learning the Answer? *Australian Journal of Engineering Education*, **3**(8), 2003, pp. 2-16.
41. S. Bell, Project-Based Learning for the 21st Century: Skills for the Future, *The Clearing House*, **83**(2), 2010, pp. 39-43.
42. J. Uziak, A project-based learning approach in an engineering curriculum, *Global Journal of Engineering Education*, **18**(2), 2016, pp. 119-123.
43. J. Perrenet, P. Bouhuijs, and J Smits, The Suitability of problem-based learning for engineering education: theory and practice, *Teaching in Higher Education*, **5**(3), 2000, pp. 345-358.
44. I. Rios, A. Cazorla, J. Diaz-Puente, and J. Yague, Project-based learning in engineering higher education: two decades of teaching competences in real environments, *Procedia Social and Behavioral Sciences*, **2**(2), 2010, pp. 1368-1378.

45. S. Han, B. Yalvac, M. M. Capraro, and R. M. Capraro, In-service teachers' implementation and understanding of STEM project based learning, *Eurasia Journal of Mathematics, Science & Technology Education*, **11**(1), 2015, pp. 63-76.
46. J. H. Labeause, LibQUAL+™ in a problem-based learning (PJBL) medical school, *Journal of Library Administration*, **40**(3-4), 2004, pp. 59-72.
47. S. Ahlfeldt, S. Mehta, and T. Sellnow, Measurement and analysis of student engagement in university classes where varying levels of PJBL methods of instruction are in use, *Higher Education Research & Development*, **24**(1), 2005, pp. 5-20.
48. L. Dinca and C. Voinescu, "Cross-functional teams and their role in increasing competitiveness of the organizational partnerships", *Proceedings of European Integration Realities and Perspectives*, **7**, 2012, pp. 453-459.
49. M. Laal and P. Salamanti, Lifelong learning; why do we need it", *Procedia - Social and Behavioral Sciences,* **31**, 2012, pp. 399-403.
50. W. Hart, In focus/mentoring nurturing relationships provide many benefits", *Leadership in Action*, **29**(1), 2009, pp. 17-20.
51. M. Cortez, *Weber State's Girls Welding Camp harnesses 'power of lightning*, https://www.deseret.com/2018/7/12/20648917/weber-state-s-girls-welding-camp-harnesses-power-of-lightning#emily-curtis-welds-during-girls-welding-camp-the-art-science-of-metalwork-at-weber-state-university-in-ogden-on-tuesday-july-10-2018, Accessed April 15, 2020.
52. J. Manley, *Haiku Fence Detail*, https://www.jasonmanley.com/?attachment_id=631, Accessed April 15, 2020.
53. R. Fleder, "On Creating Creative Engineers". Engineering Education, 77(4), 222–227 (1987).
54. American Society of Engineering Education, "The Green Report: Engineering education for a changing world". *ASEE*, Washington DC, (1994).
55. ABET, "Criteria for Accrediting Engineering Programs". *Engineering Accreditation Commission of the Accreditation Board of Engineering and Technology*, Baltimore, Maryland, (2001).
56. K. Kazerounian, S. Foley, "Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions". *Journal of Mechanical Design*, 129, 2007.
57. D. J. Wilde, 1993, "Changes Among ASEE Creativity Workshop Participants," J. Eng. Educ., 82(3), 167–170.
58. J. Shin, A. Grant, "When Putting Off Work Pays Off: The Curvilinear Relationship Between Procrastination and Creativity", Academy of Management Journal, 0, 2020.
59. C. Taylor, Climate for Creativity: Report of the Seventh National Research Conference on Creativity. Elsevier. 2013
60. J. Daley, "Five things to Know about Roger Bannister, the First Person to Break the 4-minute Mile", Smithsonian Magazine, March 15, 2018.
61. C. Mueller, "*Creativity in Science: Fostering Failure*," *Potomoc Institute: Science, Technology, Engineering, and Policy Studies*. [online journal]. URL: http://www.potomacinstitute.org/steps/component/content/article?id=18:creativity-in-science-fostering-failure [retrieved March 25, 2021].

62. S. Ambrose, M. Lovett, M. Bridges, M. DiPietro, & M. Norman, *How Learning Works: Seven Research-Based Principles for Smart Teaching*. San Francisco, CA: Jossey-Bass, 2010.
63. V. Servant-Miklos, "Fifty years on: A retrospective on the world's first problem-based learning programme at McMaster University Medical School", *Health Professions Education*, 5(1), 2019, 3-12.
64. M. Noordin, et. al. "Problem-Based Learning (PJBL) and Project-Based Learning (PJBL) in engineering education: a comparison." Proceedings of the IETEC'11 Conference, Kuala Lumpur, Malaysia, 2011.
65. S. Kalpakjian and S. Schmid, *Manufacturing Engineering and Technology*, New Jersey: Pearson, 2014.
66. G. Bruce, W. Dalton, J. Neely, and R. Kibbe, *Modern Materials and Manufacturing Processes*, New Jersey: Pearson, 2004.
67. J. Reeves, E. Williams, C. Plouffe, C. Staples, W. Carlucci, R. Smith, Y. Hammi, W. Whittington, D. Dickel, Y.-C. Liu, "Combined experimental and computational failure and fatigue analysis of a socket drive adapter", *Journal of Failure Analysis and Prevention*, 21, 2021, 1434-1444.
68. M.J. Schneider and M.S. Chatterjee, "Introduction to surface hardening of steels", *ASM Handbook*, Volume 4A, *Steel Heat Treating Fundamentals and Processes*, J. Dossett and G.E. Totten, editors, ASM International, 2013.
69. E. Oberg, F. Jones, H. Horton, & H. Ryffel, (1988). *Machinery's handbook: A reference book for the mechanical engineer, designer, manufacturing engineer, draftsman, toolmaker, and machinist*. New York: Industrial Press.
70. AISI 1008 Steel, MatWeb Material Property Data, available: http://www.matweb.com/search/datasheet.aspx?MatGUID=145867c159894de286d4803a0fc0fe0f&ckck=1.
71. J. Šimon, M. Bulko, "A Simple Mathematical Model of Cyclic Circadian Learning", *Journal of Applied Mathematics*, vol. 2014, Article 592587, 9 pages, 2014. https://doi.org/10.1155/2014/592587
72. A. Atkinson, R. Shiffrin, Mathematical Models for Memory and Learning, *Psychology Series: Institute for Mathematical Studies in the Social Sciences*, Technical Report No. 79, Stanford University, 1965.
73. K. Malmberg, J. Raaijmakers, & R. Shiffrin, 50 years of research sparked by Atkinson and Shiffrin (1968). *Mem Cogn* 47, 561–574, 2019. https://doi.org/10.3758/s13421-019-00896-7
74. S. Shikaa & J. Ajai, A Mathematical Model to Study the Human Brain Information Processing Dynamics. *American Journal of Applied Mathematics*. 3. 233. 10.11648/j.ajam.20150305.15.
75. W.J. Hicklin, A model for mastery learning based on dynamic equilibrium theory. *Journal of Mathematical Psychology, 13*(1), 79–88, 1976.
76. R. Bush, F. Mosteller, A Mathematical Model for Simple Learning. In: Fienberg S.E., Hoaglin D.C. (eds) *Selected Papers of Frederick Mosteller. Springer Series in Statistics.* Springer, New York, NY, 2006 https://doi.org/10.1007/978-0-387-44956-2_12

77. R. Anderson, A Neuromathematical Model of Human Information Processing and its applications to Science content acquisition, *Journal of Research in Science Teaching*, Vol. 20, NO. 7, PP. 603-620, 1983.
78. Burros, R. H. Some criticisms of "A mathematical model for simple learning." *Psychological Review, 59*(3), 234–236,1952. https://doi.org/10.1037/h0057645
79. P. Preece, Comments and Criticism Mathematical Modeling of Learning, *Journal of Research in Science Training*, Vol. 21, NO. 9, PP. 953-955. 1984
80. C. Fey, An Investigation of some Mathematical Models for Learning. *Journal of experimental psychology* 61.6 (1961): 455-61. *ProQuest.* Web. 9 Sep. 2021.
81. D. Burini, S. De Lillo, L. Gibelli, Collective learning modeling based on the kinetic theory of active particles, *Physics of Life Reviews*, Volume 16, Pages 123-139, 2016.
82. I. Ormazábal, F. Borotto, H. Astudillo, An agent-based model for teaching–learning processes, *Physica A: Statistical Mechanics and its Applications*, Volume 565, 2021, 125563, ISSN 0378-4371,
83. X. Wu, Y. Zhang, X. Wu, and W. Sun, A Nonlinear Dynamic Model for Individual Learning with Plateau Phenomenon. *In Proceedings of the 2020 11th International Conference on E-Education, E-Business, E-Management, and E-Learning (IC4E 2020)*. Association for Computing Machinery, New York, NY, USA, 109–115. DOI:https://doi.org/10.1145/3377571.3377575
84. W. Fredrick, & H. Walberg. Learning as a function of time. Journal of Educational Research, 73, 183-1 94, 1980.
85. B. Aldridge, A mathematical model of mastery learning. *Journal of Research in Science Teaching*, 20(1), 1-17, 1983.
86. B. Aldridge, K. Johnston, Examining a mathematical model of mastery learning in a classroom setting, *Journal of Research in Science Teaching*, Vol. 22, NO. 6, PP. 543-554, 1985.
87. J. Logan, *Applied Mathematics* (4th Ed). Wiley, 2013.
88. V. Servant-Miklos, Fifty Years on: A Retrospective on the World's First Problem-based Learning Programme at McMaster University Medical School, *Health Professions Education*, 5(1), 2019, Pages 3-12, ISSN 2452-3011, https://doi.org/10.1016/j.hpe.2018.04.002.
89. T. Schmader & M. Johns, Converging Evidence That Stereotype Threat Reduces Working Memory Capacity. *Journal of personality and social psychology*. 85. 440-52, 2003. 10.1037/0022-3514.85.3.440.
90. K. Rainey, M. Dancy, R. Mickelson, *et al.* Race and gender differences in how sense of belonging influences decisions to major in STEM. *IJ STEM Ed* **5,** 10, 2018.
91. N. Youssef, et al. "The Effects of Trauma, with or without PTSD, on the Transgenerational DNA Methylation Alterations in Human Offsprings." *Brain sciences* vol. 8,5 83. 8 May. 2018, doi:10.3390/brainsci8050083
92. M. Foss, Y.-C. Liu, and S. Yarahmadian, "An evaluation of mathematical models and stability analysis of learning based on reaction kinetics", Proceedings of the International Conference on Engineering, Science and Technology (IConEST), October 13-16, 2022, Austin, TX, USA.

93. J. Krajcik, & P. Blumenfeld. 2005. Project-Based Learning. In R. Sawyer (Ed.), The Cambridge Handbook of the Learning Sciences (Cambridge Handbooks in Psychology, pp. 317-334). Cambridge: Cambridge University
94. National Academies of Sciences. Engineering, and Medicine; Policy and Global Affairs; Board on Higher Education and Workforce; Committee on Effective Mentoring in STEMM; Dahlberg ML, Byars-Winston A, editors. Washington (DC): National Academies Press (US); 2019 Oct 30.
95. United States Bureau of Labor Statistics. Labor Force Statistics from the Current Population Survey: Employed persons by detailed occupation, sex, race, and Hispanic or Latino ethnicity, [Online]. [Accessed 5 April, 2022]. Available from: https://www.bls.gov/cps/cpsaat11.htm.
96. United States Department of Agriculture Forest Service. Pando. [Online]. [Accessed 5 April, 2022] Available from: https://www.fs.usda.gov/detail/fishlake/home/?cid=STELPRDB5393641
97. J.A. Plucker, G.R. Waitman, K.A. Hartley, *Education and Creativity*, Editor(s): Mark A. Runco, Steven R. Pritzker, Encyclopedia of Creativity (Second Edition), Academic Press, 2011, Pages 435-440, ISBN 9780123750389.